THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 35. Dec. 1922. INSTITUTION NOTES. [ISSUED WITH No. 313 OF THE JOURNAL.]

Honorary Member.

At the Ordinary Meeting of the Institution on the 13th November the President announced that the Council had elected Professor J. A. Fleming, M.A., D.Sc., F.R.S., an Honorary Member of the Institution.

Anti-Aircraft Battalion, Royal Engineers (T.A.).

The Secretary of the Institution has been requested to give publicity to the following:

Members of the Institution are invited to make application to join the recently formed (11th) A.A. Battalion, Royal Engineers (Territorial Army), whose duties will include the manning of searchlights, sound locaters and observer sections connected with the air defences of London. This unit, which is under the command of Lieut.-Colonel K. Edgcumbe, late of the London Electrical Engineers, is closely identified with that Corps and has taken over its former headquarters in Regency-street, Westminster. The Battalion comprises four companies and about 800 of all ranks. Practically all the officers, and a very large proportion of other ranks, were members of the Corps of London Electrical Engineers.

In view of the fact that the Corps of London Electrical Engineers was founded by the late Dr. John Hopkinson, then President, under the patronage of the Institution, the Officer Commanding hopes that every member of the Institution will do his utmost to encourage the younger members to join the new Battalion, and thus, in the words of Lord Kelvin, the first Hon. Colonel of the London Electrical Engineers, "promote the utilization of the patriotism and abilities of electrical engineers for national defence."

Full particulars can be obtained from the headquarters of the Battalion, 46 Regency-street, Westminster, S.W. 1.

Associate Membership Examination Results (October, 1922).

Passed.

Atkins, R. E.	Lye, D. H. C.
Austin, C.	McClean, T.
Bleach, C. C.	Morrish, H. E.
Cameron-Kirby, C.	Pennell, E. R.
Debley, W. J. F.	Smith, C. H.
Gorton, E. J.	Taylor, E. H.
Gresswell, W. F.	Telfer, F. P. G.
Herbert, E. D. A.	Waizbom, H.
Hine, F. W.	Wilkins, C.
Jones, I. L.	Williams, T.

Passed in Part II.

Badhni-Valla, J. N.	Randall, A. J.
Braendle, E. W.	West, F. W. J.
Wright, R.	

Passed in Part I.

Bee, O. K.	Weston, N. C.

[The results relating to candidates who sat for the Examination abroad will be published later.]

Officers of Corps of Royal Engineers.

Passed.

Abraham, 2nd Lieut. T. E.	Lowe, 2nd Lieut. J. H. B.
Bader, Lieut. E.	Lucas, 2nd Lieut. A. R. S.
Baker, 2nd Lieut. G. L.	McCandlish, 2nd Lieut. J. E. C.
Benner, 2nd Lieut. P. K.	Macdonald, 2nd Lieut. D. G. G.
Beyts, 2nd Lieut. W. D. H.	McDonald, 2nd Lieut. E.
Bourne, 2nd Lieut. H. J.	Mackay, 2nd Lieut. K.
Carden, 2nd Lieut. P. B. H.	McMullen, 2nd Lieut. D.
Cavendish, 2nd Lieut. H. P.	MacTier, 2nd Lieut. K. F.
Chase, Lieut. J. L. H.	Martin, 2nd Lieut. C. J. M.
Chevis, Lieut. W. J. C.	Millar, 2nd Lieut. R. K.
Churchill, Lieut. A. R.	Moscardi, 2nd Lieut. H. L.
Clark, 2nd Lieut. G. C.	Moss, 2nd Lieut. G. H. B.
Clarke, 2nd Lieut. G. G. S.	Oborne, 2nd Lieut. T. D.
Cleeve, 2nd Lieut. D. W. A.	O'Donnell, 2nd Lieut. H. M.
Cole, 2nd Lieut. W. S.	Palmer, 2nd Lieut. G. A.
Colvin, 2nd Lieut. E.	Philbrick, 2nd Lieut. G. E. H.
Cook, 2nd Lieut. E. F. B.	Prentice, 2nd Lieut. M. R. R.
Davidson-Houston, 2nd Lieut. J. V.	Ransford, Capt. A. J.
Doelberg, 2nd Lieut. J. F.	Rycroft, 2nd Lieut. D. M.
Drake-Brockman, 2nd Lieut. A. G.	Saegert, 2nd Lieut. J. M.
Fraser, 2nd Lieut. D. G.	Scullard, 2nd Lieut. H. R.
Freeman, 2nd Lieut. R. C.	Smith, 2nd Lieut. W. A. R.
Gayer, Lieut. E. H. T.	Steel, 2nd Lieut. C. D.
Hancock, 2nd Lieut. L. F.	Stowell, 2nd Lieut. E. C. S.
Havers, 2nd Lieut. R. H.	Stowell, 2nd Lieut. L. H.
Healing, 2nd Lieut. W. R.	Swettenham, 2nd Lieut. N. A. M.
Hext, 2nd Lieut. F. M.	Tuck, 2nd Lieut. G. N.
Holloway, 2nd Lieut. R. E.	Veitch, 2nd Lieut. W. L. D.
Hudson, 2nd Lieut. S. G.	Walker, 2nd Lieut. A. A. C.
Jennings, 2nd Lieut. G. W. D.	Whitehorn, 2nd Lieut. E. W. L.
Kay, 2nd Lieut. H. S.	Wilkinson, 2nd Lieut. P. L.
Laurence, 2nd Lieut. E. R.	Wright, 2nd Lieut. H. W.
Laurence, 2nd Lieut. R. A.	
Leese, 2nd Lieut. J. F. M.	
Logan, 2nd Lieut. A. R.	

Committees, 1922–1923.

Among the Committees appointed by the Council for 1922–23 are the following:—

INFORMAL MEETINGS.

The President.

Mr. J. F. Avila.	Mr. A. F. Harmer.
Mr. J. R. Bedford.	Mr. E. F. Hetherington.
Mr. A. B. Eason.	Mr. E. W. Moss.
Mr. R. Grierson.	Mr. F. Pooley.

Mr. W. E. Warrilow.

And

The Chairman of the Papers Committee.
The Chairman of the London Students' Section.

LIBRARY AND MUSEUM.

The President.

Colonel R. E. Crompton, C.B.	Mr. W. M. Mordey.
Mr. P. V. Hunter, C.B.E.	Sir A. M. Ogilvie, K.B.E., C.B.
Prof. E. W. Marchant, D.Sc.	Mr. C. C. Paterson, O.B.E.

LOCAL CENTRES.

The President.

Mr. F. G. C. Baldwin.	Mr. P. V. Hunter, C.B.E.
Mr. A. S. Barnard.	Prof. E. W. Marchant, D.Sc.
Prof. W. Cramp, D.Sc.	Sir W. Noble.
Sir J. Devonshire, K.B.E.	Mr. A. Page.
Mr. A. S. Hampton.	Mr. F. Tremain.
Mr. E. C. Handcock.	Mr. C. H. Wordingham, C.B.E.
Mr. J. S. Highfield.	

"SCIENCE ABSTRACTS."

The President.

Mr. Ll. B. Atkinson.	Mr. C. C. Paterson, O.B.E.
Mr. W. M. Mordey.	Dr. A. Russell.

And	*Representing*
Dr. D. Owen .. / Mr. T. Smith ..	The Physical Society of London.

SHIP ELECTRICAL EQUIPMENT.

The President.

Mr. J. H. Collie.	Mr. N. W. Prangnell.
Mr. B. M. Drake.	Major A. P. Pyne.
Mr. A. Henderson.	Mr. S. G. C. Russell.
Mr. J. W. Kempster.	Mr. T. A. Sedgwick.
Mr. J. F. Nielson.	Mr. C. H. Wordingham, C.B.E.

And	*Representing*
Sir W. S. Abel, K.B.E. .. / Mr. J. T. Milton ..	Lloyd's Register of Shipping.
Two representatives	British Electrical and Allied Manufacturers' Association.
Mr. T. Carlton ..	Board of Trade.
Mr. W. Cross ..	Electrical Contractors' Association.
Mr. J. Foster King	British Corporation for the Survey and Registry of Shipping.

SHIP ELECTRICAL EQUIPMENT—*continued.*

Mr. J. Lowson ..	Institution of Engineers and Shipbuilders in Scotland. Electrical Contractors' Association of Scotland.
Mr. A. W. Stewart	Institution of Naval Architects.
Mr. H. Walker, O.B.E. ..	N.E. Coast Institution of Engineers and Shipbuilders.

WIRELESS SECTION.

Professor G. W. O. Howe, D.Sc. (*Chairman*).

The President.

Mr. B. Binyon, O.B.E.	Capt. H. J Round, M.C.
Mr. S. Brydon, D.Sc.	Dr. A. Russell.
Mr. R. C. Clinker.	Capt. H. R. Sankey, C.B., C.B.E., R.E.
Dr. W. H. Eccles, F.R.S.	Mr. R. L. Smith-Rose.
Prof. C. L. Fortescue, O.B.E.	Mr. A. A. C. Swinton, F.R.S.
Mr. G. H. Nash, C.B.E.	Mr. L. B. Turner.
Mr. C. C. Paterson, O.B.E.	
Mr. J. St. Vincent Pletts.	

And	*Representing*
Capt. C. E. Kennedy-Purvis, R.N. ..	Admiralty.
Lt.-Col. H. Clementi Smith, D.S.O. ..	War Office.
Major H. P. T. Lefroy, D.S.O., M.C.	Air Ministry.
Mr. E. H. Shaughnessy, O.B.E.	Post Office.

WIRING RULES.

The President.

Mr. Ll. B. Atkinson.	Mr. P. V. Hunter, C.B.E.
Mr. J W Beauchamp.	Mr. S. W. Melsom.
Mr. H. J. Cash.	Mr. J. F. Nielson.
Mr. J. R. Cowie.	Major A. P. Pyne.
Mr. W. Cross.	Mr. E. Ridley.
Mr. J. Frith.	Mr. C. P. Sparks, C.B.E.
Dr. C. C. Garrard.	Mr. C. H. Wordingham, C.B.E.

And	*Representing*
Mr. E. G. Batt .. / Mr. H. H. Berry .. / Mr. J. R. Dick .. / Mr. A. R. Everest / Mr. C. Rodgers ..	British Electrical and Allied Manufacturers' Association.
Mr. W. F. Bishop	Cable Makers' Association.
Sir T. O. Callender / Mr. J. F. W. Hooper	Cable Makers (unofficially).
Mr. W. R. Rawlings / Mr. S. H. Webb ..	Electrical Contractors' Association.
Mr. E. J. B. Lowdon	Electrical Contractors' Association of Scotland.
Mr. B. M. Drake ..	Contractors (unofficially).
Mr. A. C. Cockburn / Mr. S. G. C. Russell / Mr. A. L. Taylor ..	Fire Offices (unofficially).
Mr. J. Christie .. / Mr. F. W. Purse ..	Incorporated Municipal Electrical Association.
Mr. E. T. Ruthven Murray	Incorporated Association of Electric Power Companies.
Mr. O. M. Andrews	Conference of Chief Officials of the London Electric Supply Companies.
Mr. J. M. Crowdy ..	Association of Supervising Electricians.

SECTIONAL COMMITTEES.

Lighting and Power.

The President.

Mr. J. W. Beauchamp.
Mr. J. R. Bedford.
Mr. R. A. Chattock.
Mr. R. Grierson.
Mr. A. F. Harmer.
Mr. E. T. Ruthven Murray.
Mr. A. Page.
Mr. G. W. Partridge.
Mr. C. P. Sparks, C.B.E.
Mr. W. B. Woodhouse.

Electricity in Mines.

The President.

Mr. W. A. Chamen.
Dr. C. C. Garrard.
Mr. J. A. B. Horsley.
Mr. W. C. Mountain.
Mr. W. H. Patchell.
Mr. W. M. Selvey.
Mr. C. P. Sparks, C.B.E.
Prof. W. M. Thornton, D.Sc., O.B.E.
Mr. W. B. Woodhouse.

Traction.

The President.

Sir J. Devonshire, K.B.E.
Mr. H. W. Firth.
Lt.-Col. F. A. Cortez Leigh.
Mr. F. Lydall.
Mr. A. H. W. Marshall.
Mr. G. W. Partridge.
Mr. J. Sayers.
Mr. R. T. Smith.
Mr. B. Welbourn.

Electro-Chemistry and Electro-Metallurgy.

The President.

Mr. W. A. Chamen.
Mr. W. R. Cooper.
Prof. W. Cramp, D.Sc.
Mr. S. E. Fedden.
Mr. W. M. Mordey
Mr. W. M. Morrison.
Mr. J. Swinburne, F.R.S., and 2 members to be co-opted by the Committee.

Telegraphs and Telephones.

The President.

Sir Charles Bright, F.R.S.E.
Mr. H. G. Brown.
Dr. W. H. Eccles, F.R.S.
Mr. S. Evershed.
Mr. H. H. Harrison.
Sir W. Noble.
Mr. T. F. Purves.
Mr. F. Ryan.
Mr. J. Sayers.
Mr. F. Tremain.

Representatives of The Institution on Other Bodies.

The following is a list of representatives of the Institution on other bodies and the dates on which they were appointed

Birmingham Chamber of Commerce:

Mr. S. T. Allen (27 March, 1919).

Bradford Public Libraries Committee:

Mr. T. Roles (27 Feb., 1919).

Bristol University:

Mr. H. F. Proctor (6 Dec., 1917).

British Electrical and Allied Industries Research Association:

Mr. Ll. B. Atkinson (2 April, 1919).
Dr. C. C. Garrard (30 Oct 1919).
Mr. F. Gill, O.B.E. (2 Nov., 1922).
Mr. C. C. Paterson, O.B.E. (4 Oct., 1917).
Mr. R. T. Smith (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (4 Oct., 1917).
Mr. C. H. Wordingham, C.B.E. (4 Oct., 1917).

Sectional Committee on Electric Control Apparatus Research:

Mr. C. H. Wordingham, C.B.E. (22 Nov., 1920).
Major H. C. Gunton (2 Feb., 1921).

British Electrical Development Association:

Mr. R. Hardie (27 Jan., 1921).
Mr. H. J. Cash (19 Jan., 1922).
Mr. C. H. Wordingham, C.B.E. (18 Sept., 1919).

British Empire Exhibition, 1924 (Electrical and Allied Engineering Committee):

Sir A. M. Ogilvie, K.B.E., C.B. (23 June, 1922).

British Engineering Standards Association:

Main Committee:

Col. R. E. Crompton, C.B. (2 April, 1914).
Sir John Snell (2 April, 1914).
Mr. C. H. Wordingham, C.B.E. (26 Feb., 1920).

Sectional Electrical Committee:

Mr. F. Gill, O.B.E. (21 May, 1914).
Mr. J. S. Highfield (21 May, 1914).
Mr. R. T. Smith (21 May, 1914).
Mr. W. B. Woodhouse (19 Dec., 1918).
Mr. C. H. Wordingham, C.B.E. (18 Nov., 1915).

Sectional Committee on British Standards in Colonial and Foreign Trade:

Mr. C. P. Sparks, C.B.E. (26 Oct., 1916).

Sectional Committee on Machine Parts and their Gauging and Nomenclature:

Mr. J. H. Rider (8 Feb., 1917).

Electrical Nomenclature and Symbols Sub-Committee

Mr. C. C. Paterson, O.B.E. (8 Jan., 1920).

Overhead Transmission Lines Material Sub-Committee

Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

Pipe Flanges Sub-Committee:

Mr. W. M. Selvey (14 April, 1921).

Panel on Steel Conduits for Electric Wiring:

Mr. H. J. Cash (28 Sept., 1922).
Mr. J. M. Crowdy (28 Sept., 1922).

Conference on Standardization of Ball and Roller Bearings:

Mr. W. M. Selvey (26 July, 1921).

Corrosion Research Committee, Institute of Metals:

Mr. W. M. Selvey (18 May, 1922).

Darlington Board of Invention and Research:

Mr. R. M. Longman (15 May, 1919).
Mr. J. R. P. Lunn (15 May, 1919).
Mr. H. G. A. Stedman (15 May, 1919).

Fuel Economy Committee, British Association:

Mr. C. H. Wordingham, C.B.E. (9 Jan., 1919).

Imperial College of Science and Technology, Governing Body:

Mr. W. M. Mordey (30 Oct., 1919).

Imperial Mineral Resources Bureau Conference:

Mr. J. H. Rider (23 Jan., 1919).
Mr. W. B. Woodhouse (23 Jan., 1919).

Copper Committee:

Mr. B. Welbourn (18 Sept., 1919).

Miscellaneous Minerals Committee:

Prof. E. Wilson (18 March, 1920).

Institution of Civil Engineers, Engine and Boiler Testing Committee:

Mr. R. A. Chattock (19 Oct., 1922).
Mr. C. P. Sparks, C.B.E. (19 Oct., 1922).

International Illumination Commission, British National Illumination Committee:

Prof. W. C. Clinton (13 Dec., 1917).
Mr. K. Edgcumbe (27 Nov., 1913).
Mr. Percy Good (18 Sept., 1919).
Mr. H. T. Harrison (27 Nov., 1913).
Prof. J. T. MacGregor-Morris (27 Nov., 1913).

International Navigation Congress, 1923, General Organization Committee:

Mr. F. Gill, O.B.E. (2 Feb., 1922).

International Scientific Unions:

Committee on International Union in Physics:

Dr. A. Russell (18 March, 1920).

Committee on International Union in Radio-Telegraphy:

Dr. W. H. Eccles, F.R.S. (18 March, 1920).
Prof. G. W. O. Howe, D.Sc. (18 March, 1920).
Prof. E. W. Marchant, D.Sc. (18 March, 1920).

International Smoke Abatement Exhibition, 1922:

Mr. J. W. Beauchamp (26 July, 1921).
Mr. J. S. Highfield (26 July, 1921).

Leeds Civic Society:

Mr. E. C. Wallis (27 March, 1919).

Leeds Municipal Technical Library Committee:

Mr. W. B. Woodhouse (19 Dec., 1918).

Metalliferous Mining (Cornwall) School, Governing Body:

Mr. J. S. Highfield (18 Sept., 1919).

Munitions Inventions Department, Nitrogen Products Committee:

Sir John Snell (12 Oct., 1916).

Munitions, Ministry of, Disposal of Surplus Government Property:

Mr. J. S. Highfield (13 Feb., 1919).

National Committee for Physics (Royal Society)

Dr. A. Russell (16 Dec., 1920).

National Committee in Radio-Telegraphy (Royal Society):

Dr. W. H. Eccles, F.R.S. (4 Aug., 1920).
Prof. E. W. Marchant, D.Sc. (4 Aug., 1920).

National Physical Laboratory, General Board:

Mr. Ll. B. Atkinson (21 Oct., 1920).
Mr. C. H. Wordingham, C.B.E. (22 Nov., 1917).

Paris Conference on E.H.T. Lines:

Mr. P. V. Hunter, C.B.E. (26 July, 1921).
Mr. E. B. Wedmore (26 July, 1921).
Mr. W. B. Woodhouse (26 July, 1921).

Paris Conference on Weights and Measures:

Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S. (14 April, 1921).
Dr. A. Russell (14 April, 1921).

Professional Classes Aid Council:

Mr. W. B. Esson (26 July, 1921).

Röntgen Society Advisory Committee for British X-ray Industry:

Dr. W. H. Eccles, F.R.S. (21 Feb., 1918).
Mr. J. E. Taylor (21 Feb., 1918).

Royal Engineer Board:

Mr. C. H. Wordingham, C.B.E. (7 April, 1921).

Scientific and Industrial Research Advisory Council, Engineering Committee:

Mr. J. S. Highfield (9 March, 1916).

Scientific Societies, Conjoint Board of:

Mr. C. C. Paterson, O.B.E. (9 Dec., 1920).
Dr. A. Russell (9 Dec., 1920).

Education Committee:

Dr. A. Russell (12 Oct., 1916).

Society of Radiographers:

Dr. A. Russell (25 May, 1922).

Transport Ministry, Advisory Panel and Committees:

Mr. Ll. B. Atkinson (30 Oct., 1919).
Sir J. Devonshire, K.B.E. (30 Oct., 1919).
Mr. J. S. Highfield (30 Oct., 1919).
Mr. R. T. Smith (30 Oct., 1919).
Sir John Snell (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (30 Oct., 1919).
Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

War Office Committee on Engineer Organization:

Mr. C. H. Wordingham, C.B.E. (10 April, 1919).

Women's Engineering Society:

Mr. A. P. M. Fleming, C.B.E. (14 April, 1921).

THE INSTITUTION OF ELECTRICAL ENGINEERS.

No 36. JAN. 1923. INSTITUTION NOTES. [ISSUED WITH No. 314 OF THE JOURNAL.]

Local Honorary Secretaries Abroad.

The Council have appointed Mr. Gano Dunn to be Local Honorary Secretary of the Institution for the United States of America, and Mr. M. L. Kristiansen for Norway.

Summer Meeting, 1923.

The Council have accepted an invitation from the Committee of the North-Western Centre to hold a Summer Meeting of the Institution in Manchester, Liverpool and North Wales from 5th to 8th June, 1923. Full particulars will be circulated later.

Members Visiting the U.S.A.

The attention of members is drawn to an arrangement between the Institution and the American Institute of Electrical Engineers for the mutual granting of facilities and privileges as Visiting Members to members of the two societies visiting each other's country.

Members who intend to visit the United States of America and wish to avail themselves of this arrangement should apply to the Secretary of the Institution for a letter of introduction to the American Institute of Electrical Engineers, stating in what branch of the profession they are engaged and giving the name of the firm or company (if any) with which they are connected.

International Conference on E.H.T. Power Transmission.

The Proceedings of the above Conference, which was held at Paris in November, 1921, and at which 12 countries were represented, have recently been published by the Union des Syndicats de l'Electricité.

The Proceedings comprise 1 200 pages and 350 illustrations, and contain: (1) an introductory note in regard to the aims and work of the Conference; (2) a general account of the proceedings by M. Boucherot; (3) the full text of the 68 Reports presented to the Conference; and (4) revised reports of the discussions.

The Proceedings will not be reprinted, and only a limited number of copies will be available for non-subscribers to the Conference. Any member of the Institution desirous of obtaining a copy should therefore make early application to the Union des Syndicats de l'Electricité, 25, Boulevard Malesherbes, Paris. The price is 100 francs per copy.

Informal Meetings.

The following Informal Meetings have been held:

33RD INFORMAL MEETING (6TH NOVEMBER, 1922).

Chairman: Mr. F. Gill, O.B.E.

Subject of Discussion: "The Importance of Commercial Knowledge to the Engineer" (introduced by Mr. F. Gill, President).

Speakers: Messrs. F. Pooley, W. E. Rogers, F. H. Masters, L. W. Phillips, W. H. Lawes, R. W. Hughman, A. Wright, A. F. Harmer, P. Rosling, G. V. Twiss, P. Dunsheath, E. F. Hetherington, R. C. Andersen, F. A. Sclater, R. Grierson, and A. Rosen.

34TH INFORMAL MEETING (20TH NOVEMBER, 1922).

Chairman: Mr. W. E. Warrilow.

Subject of Discussion: "Electric Light Wiring" (introduced by Mr. F. J. Pearce).

Speakers: Messrs. F. Peake Sexton, A. F. Harmer, W. E. Rogers, W. L. Wreford, W. F. Bishop, P. Rosling, W. Fanghanel, E. H. Freeman, L. M. Jockel, A. G. Hilling, A. T. Smee, E. Turle, C. J. Banster, P. Dunsheath, F. E. Phillips, P. D. Dale, M. Whitgift, C. T. Walrond, J. R. Bedford, G. J. D. Scott, and W. E. Warrilow.

35TH INFORMAL MEETING (4TH DECEMBER, 1922).

Chairman: Mr. J. F. Avila.

Subject of Discussion: "An Electrical Installation at a Model Farm" (introduced by Mr. F. A. Sclater).

Speakers: Messrs. R. Borlase Matthews, W. E. Rogers, H. F. Young, J. Coxon, C. A. Edwards, W. J. Minton, A. H. Dixon, W. E. Warrilow, C. T. Walrond, A. G. Hilling, P. Dunsheath, J. F. Caine, F. Pooley, W. L. Wreford, J. R. Bedford, B. Shallis, E. B. Rook, and H. W. Richardson.

36TH INFORMAL MEETING (18TH DECEMBER, 1922).

Chairman: Mr. J. R. Bedford.

Subject of Discussion: "Time Switches" (introduced by Mr. E. E. Sharp).

Speakers: Messrs. F. B. Nathan, W. L. Wreford, C. T. Walrond, F. Pooley, J. R. Bedford, W. E. Rogers, A. G. Hilling, G. D. Malcolm, A. Kirk, R. V. Hook, H. H. Long, F. R. C. Rouse, J. F. Avila, and G. J. D. Scott.

37TH INFORMAL MEETING (8TH JANUARY, 1923).

Chairman: Mr. R. Grierson.

Subject of Discussion: "The Protection of Inventions by Letters Patent" (introduced by Mr. E. W. Moss)

Speakers: Messrs. W. E. Rogers, A. F. Harmer, E. F. Hetherington, J. R. Bedford, P. G. A. H. Voigt, A. G. Evans, W. L. Wreford, C. S. Parsons, J. L. Girling, M. Whitgift, A. S. Carnegie, F. W. Foster, R. V. Hook, C. L. Arnold, G. J. D. Scott, and R. Grierson.

"Les Annales des Postes, Télégraphes et Téléphones."

The Secretary is informed that the above publication, which for several years past has been issued every two months by the French Post, Telegraph and Telephone Department, will become from the 1st January, 1923, a monthly publication. The price will continue to be 24 francs for subscribers in France, and 27 francs for subscribers abroad. The publishers are La Libraire de l'Enseignment Technique, 3, Rue Thénard, Paris, to whom subscriptions should be sent.

The British Electrical and Allied Industries Research Association.

HALF-YEARLY REVIEW OF PROGRESS (JANUARY, 1923).

SECTION A: FIBROUS INSULATING MATERIALS.

Classification and nomenclature.—The classification of materials, uses and requirements has now been completed for all the fibrous materials and materials with a fibrous base dealt with hitherto by this Association, thus furnishing a firm foundation for future study. The detailed study of varnishes has only been commenced recently and the classification is incomplete.

Methods of testing.—Methods of testing have now been developed for all the materials dealt with and have been fully described in the publications of the Association, the work on varnished fabrics being, however, not quite complete.

Purchasing specifications.—Based on the above and the results of the numerous investigations which have been made, the Association is now drafting simplified recommendations applicable to the preparation of British Standard Purchasing Specifications in connection with all the materials in the fibrous group ripe for standardization.

Improvement of materials.—As a direct result of the attention given to certain features, improvements can already be recorded in the quality of materials manufactured. Attention is now being directed to the study of specific sources of weakness which have been traced through the work already done, and to the development of new materials having better characteristics.

Attention is being given to shellac, amongst other materials, with a view to obtaining better adhesiveness and temperature characteristics, and comparison is being made with alternative materials.

SECTION B: COMPOSITE INSULATING MATERIALS.

The experimental tests on heat-resisting properties are now practically completed, which will furnish the necessary data for the completion of a specification on these properties. A provisional classification has been made of moulding properties of composite insulating materials, and some attention has been given also to the effect of immersion in insulating oils or contact with lubricating oils.

SECTION C: PORCELAIN.

The Association is awaiting a full report from the investigators, but the following may be noted meanwhile :—

Electric strength.—A series of investigations of electric strength under momentary stresses has been practically completed, covering a temperature range from normal to 300° C., and some progress made with tests under prolonged stress.

Resistivity.—A large variety of samples varying in composition and mode of manufacture has been tested for resistivity at temperatures from 70° C. up to 1 200° C. Samples suitable for furnace work have not yet been tested.

Porosity and vitrification.—Some progress has been made in the study of porosity by electrical methods, and uniformity of vitrification by immersion in water under high pressure.

Surface deposits.—The study of surface deposits from the atmosphere has presented unexpected difficulties, but further tests are being made in co-operation with the G.P.O.

Thermal expansion.—Tests on thermal expansion have been arranged in co-operation with an interested Government Department.

Mechanical properties.—Samples are being obtained for tests on mechanical properties.

SECTION D: MICA AND MICANITE.

Micas.—Further tests have brought out important features in the study of mechanical properties of mica, especially flexibility, and a survey of these properties is now being made on a small scale.

Micanites.—Methods of studying the properties of micanite have been developed with a view to the production of a purchasing specification, and the elimination of undesirable material. Work is nearly completed on the following: Uniformity and limits of thickness; percentage of moisture, adhesive, mica and reinforcement; quality of splittings; softening temperature; moulding temperature; electric strength; permittivity; surface resistance; tensile strength.

A report on the classification of micanites, with notes on their manufacture, uses and characteristics, is about to be issued.

SECTION E: INSULATING OILS.

Electric strength and resistivity.—The detailed investigation into the relative merits of the horizontal and vertical placing of the spherical electrodes used in electric strength tests has now been completed and has shown that the horizontal arrangement is the better for the purpose.

An attempt is being made to develop a method of testing electric strength eliminating the expensive high-voltage transformer equipment now necessary.

Past research on the effect of the presence of different kinds of impurity on electric strength and resistivity has been reviewed in detail and a new series of researches commenced.

Centrifugal separation.—Further tests have been made and arranged for the investigation of the merits

of centrifugal separators for oil purification with a view to discovering the technical and commercial limitations of apparatus now available, and assisting in the development of this promising method.

Sludging tests.—Opportunity has been taken of the presence in this country of experts from the U.S.A. and the Continent to discuss the methods of sludge testing in use and under development in those countries. Attempts are being made to develop a simpler test than now in use.

Physical constants.—Reports have been received on latent heat, vapour pressure, thermal conductivity and specific heat, and are under consideration.

Thermal transference.—A report has been received on thermal transference and is under consideration.

Section F: Conductors.

Heating of buried cables.—Good progress has been made in the preparation of the Report on "Permissible Current Loading of British Standard Paper Insulated Electric Cables," being the second report on the research on the heating of buried cables, and it is hoped to present the report to the Institution of Electrical Engineers in a few weeks' time.

Wood poles for overhead lines.—A report on the tests made on single A and H poles has been issued to interested members of the Association. Progress has been made towards clearing up the numerous important questions raised by that report, and a further programme of tests will be put in hand shortly.

Overhead line materials.—Reports have been completed on the tests made under working conditions on the mechanical properties of copper and aluminium wires and cables, and galvanized steel and steel-cored aluminium cables, and it is expected that these will be published shortly.

Section G: Electric Control Apparatus.

Phenomena of switching and arcing.—The researches on oil circuit breakers are now in full activity, a unique installation of testing apparatus having been developed and erected at the Carville power station of the Newcastle-upon-Tyne Electric Supply Co., at a cost of several thousand pounds. The larger part of the original programme of experimental work has already been completed, and in view of the importance of this research to the whole industry, and especially to large users and suppliers of electricity, the Association is appealing for their co-operation so that full advantage may be taken of the exceptional opportunity at present available for further experimental research and development.

Mining switchgear.—The researches on the development and relief of pressure in mining switchgear are being continued under the auspices of the Technical Appliances Committee of the Safety in Mines Research Board, and a further report is expected shortly.

Fusible cut-outs.—A comprehensive survey of published information on fusible cut-outs has been completed and a critical résumé prepared, which will form a firm foundation for building up future research programmes. A report is in preparation on the tests made on ordinary-duty fusible cut-outs.

Air-break circuit breakers.—The continuation of researches on air-break circuit breakers awaits the provision of the necessary facilities.

Resistivity of joints and contacts.—Further tests have been made on joints in large installations of switchgear and a report is expected shortly. Arrangements have been made for continuation of the experimental researches at the National Physical Laboratory.

Research on contactors.—A programme of endurance tests on contactors has been prepared and the work awaits the provision of the necessary funds.

Section H: Corrosion Researches.

The Association continues to co-operate with the Institute of Metals, and the researches on corrosion of steam condensers are maintained in full activity. The sixth report of the Corrosion Research Committee has been received, dealing with the nature of corrosive action, the function of colloids in corrosion and the corrosion of copper.

Section J: Turbine Researches.

Nozzles research.—A further report of the work in which the Association shares is about to be published by the Institution of Mechanical Engineers.

Blading research.—The tests arranged on blading material have been practically completed and a report is awaited.

Properties of steam.—The researches on the properties of steam at high temperatures and pressures are in full activity, and other work bearing on the behaviour of steam in turbines.

Section K: Synthetic Resins.

Varnish-paper boards and tubes.—A series of tests carried out on samples from a variety of sources has shown very wide divergences of quality. Further tests are now being carried out on the more promising materials, especial attention being given to the electrical characteristics at radio frequencies and to the mechanical properties. As the result of these tests manufacturers are giving close attention to features which have been shown capable of marked improvement.

Moulded materials.—A representative collection of samples from British and foreign sources has now been made and an experimental investigation put in hand, in which the Royal Aircraft Establishment is co-operating.

Section L: Dielectrics in General.

Dielectric losses.—The investigation on dielectric losses has now been extended to radio frequencies, especial attention being given to the synthetic resin products. Work on micas has been practically completed, and a report is expected shortly on varnished fabrics.

Good progress has been made in the development and application of cathode ray tubes.

Thermal resistivity.—A considerable number of further measurements of thermal resistivity have been made showing the effect of different methods of construction of the finished product. Shortage of funds will neces-

sitate this important investigation being brought to a close at an early date.

Effect of heat on electrical insulating materials.—Recommendations for the classification and nomenclature of the heat-resisting properties of dielectrics have been prepared and transmitted to the interested Committees of the British Engineering Standards Association and the Institution of Electrical Engineers. Methods of test are being developed and made applicable to the whole range of materials in question. The same procedure is being extended to cover the effect of temperature on the electrical and mechanical properties.

Electric strength.—A preliminary report has been received on the tests made to show the relative accuracy of certain laboratory and workshop methods of testing electric strength, and bringing out some quite unexpected and important features which are receiving further attention.

Comprehensive recommendations are in preparation covering methods of testing the electric strength of all kinds of insulating materials.

Section M: Wave-form.

The preparation of a programme of experimental work awaits the results of further study of what has been done elsewhere.

Section Z: Unclassified.

Die castings.—The Association is co-operating with others in preparing a scheme of research for improvements in the manufacture and use of die castings.

Flicker in electric lamps.—An investigation has been made into the limiting conditions under which objectionable flicker is produced in electric lamps by cyclic variations of supply voltage.

Accessions to the Lending Library.

Avery, A. H. Dynamo design and construction. 8vo. 263 pp. *London, n.d.*

Broughton, H. H. The electric handling of materials. vol. 3, Electric cranes. 4to. 352 pp. *London,* 1922

Carslaw, H. S. Introduction to the mathematical theory of the conduction of heat in solids. 2nd ed. 8vo. 280 pp. *London,* 1921

Carter, F. W. Railway electric traction. 8vo. 420 pp. *London,* 1922

Cushing, H. C., *jr.* The electric vehicle hand-book. sm. 8vo. 388 pp. *New York,* [1918]

Few, H. P. Elementary determinants for electrical engineers. sm. 8vo. 98 pp. *London,* [1922]

Goudie, W. J., *D.Sc.* Steam turbines. 2nd ed. 8vo. 822 pp. *London,* 1922

Kearton, W. J. Steam turbine theory and practice. 8vo. 472 pp. *London,* 1922

Keen, R. Direction and position finding by wireless. 8vo. 376 pp. *London,* 1922

Kemp, P. Alternating current electrical engineering. [2nd ed.] 8vo. 526 pp. *London,* 1922

Lawrence, R. R. Principles of alternating currents. 8vo. 446 pp. *New York,* 1922

Main, F. W. Electric cables: a practical treatise on the construction, properties, installation and maintenance of electric cables. For junior engineers, students, and those in charge of works and factories. sm. 8vo. 111 pp. *London,* 1922

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Meares, J. W., *C.I.E.* The law relating to electrical energy in India. 2nd ed., revised. 8vo. 403 pp. *Calcutta,* 1922

Mittell, B. E. G. Continuous wave wireless telegraphy. sm. 8vo. 129 pp. *London,* 1922

Poole, H. E. Switching and switchgear. sm. 8vo. 127 pp. *London,* 1922

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Rasch, E. Electric arc phenomena. Transl. by K. Tornberg. 8vo. 210 pp. *New York,* 1913

Robinson, S. M., *U.S.N.* Electric ship propulsion. 8vo. 280 pp. *New York,* [1922]

Scott-Taggart, J. Elementary text-book on wireless vacuum tubes. 4th ed. 8vo. 262 pp. *London,* [1922]

Smith, C. F. The testing of transformers and alternating current machines. sm. 8vo. 102 pp. *London,* 1922

Tattersall, A. E. Modern developments in railway signalling. A treatise dealing with the theory and application of—(1) Track-circuiting; (2) Power signalling, and (3) Automatic train control. 8vo. 299 pp. *London,* 1921

Taylor, W. T. Electric power systems. sm. 8vo. 119 pp. *London,* 1922

Van der Bijl, H. J. The thermionic vacuum tube and its applications. 8vo. 410 pp. *New York,* [1920]

Wanamaker, E., and Pennington, H. R. Electric arc welding. 8vo. 265 pp. *New York,* [1921]

THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 37. MARCH 1923. INSTITUTION NOTES. [ISSUED WITH No. 316 OF THE JOURNAL.]

Faraday Medal.

At the Council Meeting held on the 15th February the second award of the above Medal was made to the Hon. Sir Charles Algernon Parsons, K.C.B., F.R.S., Honorary Member of the Institution.

War Thanksgiving Education and Research Fund (No. 1).

The Council have made a grant for 1923 in connection with the above Fund to Mr. R. H. Holmes, a student at the Armstrong College, Newcastle-upon-Tyne.

War Memorial Fund Scholarships.

Out of the balance of the above Fund it has been decided to establish two scholarships, each of the value of £50 per annum and tenable for three years, to provide for the education of children of members of the Institution who were killed or permanently disabled in the late War.

Applications, giving full particulars as to general and financial circumstances, should be addressed to the Secretary of the Institution, Savoy-place, Victoria-Embankment, W.C. 2.

Annual Conversazione.

The Annual Conversazione will be held at the Natural History Museum, South Kensington, by permission of the Trustees of the Museum, on Thursday, 28th June, 1923.

Ordinary Meeting, 12 April, 1923.

At the Ordinary Meeting on the 12th April, when a lecture will be given by Mr. A. G. Warren on "X-rays in Theory and Practice," Mr. E. E. Brooks will show at the conclusion of the lecture a few slides illustrating lines of electric force.

Associate Membership Examination Results (October, 1922).

SUPPLEMENTARY LIST.*

Passed :

Jenkin, R. M.	(New Zealand).
Williams, V. E.	(South Africa).
Witt, S. H.	(Melbourne, Australia).

* See Institution Notes, No. 35, page 1, December, 1922.

Specification of British Plant and Material.

At a meeting of the Council held on the 1st February, 1923, the following Resolution was passed :—

> "That in view of the present state of trade and employment the Council request members who place or who advise upon the placing of orders to specify as far as practicable that the plant and material ordered shall be of British manufacture."

International Conference on E.H.T. Lines.

The Council have appointed the following to be the representatives of the Institution at the above Conference, which will be held in Paris next October :—

Mr. W. B. Woodhouse (Senior Delegate),
Mr. P. V. Hunter, C.B.E.,
Mr. E. B. Wedmore.

In addition to the official Delegates, it is understood that the Conference will welcome the attendance of other representatives from each country taking part. Such unofficial representatives will be eligible to take part in the discussions. Those wishing to attend should send their names to M. Tribot-Laspière, 25 Boulevard Malesherbes, Paris.

Electrical Appointments Board.

The Council again desire to call attention to the Electrical Appointments Board the object of which is to find positions for unemployed members.

During the past year there has been a gradual increase in the number of applicants for posts, particularly Students who have completed their college courses.

A classified Register of such members, containing particulars of their training and experience, is available for inspection at the Institution offices and the Secretary of the Board will gladly put employers into touch with highly qualified electrical engineers in practically all branches of the profession.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the Register. Vacancies may also be reported to the Honorary Secretaries of Local Centres and Sub-Centres who will at once report such vacancies to the Secretary of the Board at the Institution Offices.

Economics of Engineering Design.

The Secretary will be glad to receive from members, for use in the Institution Library, references to books or articles dealing with or referring to the economics of engineering design.

Royal Engineers Old Comrades' Association.

Major-General Sir G. K. Scott-Moncrieff, K.C.B., K.C.M.G., C.I.E., President of the Central Committee of the Royal Engineers Old Comrades' Association, desires to ask members of the Institution, particularly ex-Royal Engineers, to assist the Association in finding employment for a large number of skilled men who have served with the R.E. Corps and whose names are now on the Employment Register of the Association.

The requirements of firms seeking reliable men will receive the prompt attention of the Association, and every effort will be made to provide trustworthy men to fill any positions offered. Men skilled in various branches of the engineering industry (including foremen of works, mechanists, electricians, store and ledger keepers, clerks, draughtsmen, instructors in field engineering, surveyors, etc.) are available and the Secretary of the Association, Mr. J. McB. Robbins, Army and Navy Mansions, 109 Victoria-street, London, S.W. 1, will be glad to receive particulars of vacancies.

Members from the Dominions and Colonies Visiting the United Kingdom.

Members from the Dominions and Colonies visiting the United Kingdom who wish to be put into touch with members of the Institution at home are invited to communicate with the Secretary, stating in what branch of the profession they are engaged and giving the name of the firm or company (if any) with which they are associated.

In this connection the Council have set up an "English-Speaking Nations Committee" whose principal duty is to take an interest in such members and visiting members from the American Institute of Electrical Engineers,

Removal from Institution Register.

At a meeting held on the 1st March, 1923, the Council ordered the name of Mr. Walter Talbot Kerr to be removed from the Register of the Institution in pursuance of Bye-Law 41 (a).

Accessions to Reference Library.

ADAMS, H. Structural design in theory and practice. 2nd ed. 8vo. 265 pp. *London*, 1923

ADMIRALTY, THE. Admiralty handbook of wireless telegraphy. 8vo. 485 pp. *London*, 1920

AINSLEY, F. J. Mast and aerial construction for amateurs, together with the method of erection and other useful information. sm. 8vo. 86 pp. *London*, 1922

ALLEN, A. H. Electricity in agriculture. sm. 8vo. 127 pp. *London*, 1922

AMERICAN ROLLING MILL COMPANY. Research and methods of analysis of iron and steel at Armco. 2nd ed. 8vo. 220 pp. *Middletown, Ohio*, 1920

ANDREWS, E. S. Alignment charts. Their principle and application to engineering formulæ. sm. 8vo. 32 pp. *London*, [1915]

BAGNALL-WILD, *Brig.-Gen.* R. K., AITCHISON, L., REMINGTON, A. A., ROWLEDGE, A. J., and THAIN, W. A. Aircraft steels and material. With an introduction by Prof. W. Ripper. 8vo. 216 pp. *London*, 1922

BEHREND, B. A. The induction motor and other alternating current motors. Their theory and principles of design. 2nd ed. 8vo. 295 pp. *New York*, 1921

BRITISH COLUMBIA: BUREAU OF MINES. Annual report of the Minister of Mines for the year ending 31st December, 1921, being an account of mining operations for gold, coal, etc., in the Province. la. 8vo. 365 pp., plates, maps, 1921. *Victoria, B.C.*, 1922

BRITISH ELECTRICAL AND ALLIED MANUFACTURERS' ASSOCIATION, THE. Terms of educational scholarships in electrical and mechanical engineering. 8vo. 8 pp. *London*, 1922

BROWNLIE, D. Boiler plant testing. 8vo. 179 pp. *London*, 1922

CARTER, F. W. Railway electric traction. 8vo. 420 pp. *London*, 1922

CHALKLEY, A. P. Diesel engines for land and marine work. With an introductory chapter by Dr. R. Diesel. 5th ed. 8vo. 347 pp. *London*, 1922

CONJOINT BOARD OF SCIENTIFIC SOCIETIES, THE. Water-power in the British Empire: The Reports of the Water-Power Committee of the C.B. of S.S. Sir Dugald Clerk, K.B.E., F.R.S. (Chairman) Prof. A. H. Gibson, D.Sc. (Secretary). sm. 8vo. 63 pp. *London*, 1922

CONSTANTINESCO, G. Theory of wave transmission. A treatise on transmission of power by vibrations. 2nd ed. 8vo. 213 pp. *London*, 1922

COURSEY, P. R. The wireless telephone. What it is, and how it works. sm. 8vo. 112 pp. *London*, 1922

DAVIDGE, H. T., and HUTCHINSON, R. W. Technical electricity. 4th ed. 8vo. 526 pp. *London*, 1922

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH. Report of the Fuel Research Board for the years 1920, 1921. Second section: Low temperature carbonisation. 8vo. 73 pp. 8 pl. *London*, 1922

DOVER, A. T. Industrial motor control. Direct current. sm. 8vo. 128 pp. *London*, 1922

EAST AFRICA PROTECTORATE. An Ordinance to make provision for the generation, transmission, delivery, sale, purchase, and use of electrical energy; and for the making and enforcing of regulations appertaining to and governing such purposes; and for the provision and enforcing of penalties for any contravention of this Ordinance or of the regulations made under it. folio. 94 pp. *Nairobi*, 1920

ELECTRICAL POWER ENGINEERS' ASSOCIATION. Report on the training of electrical power engineers.
8vo. 18 pp. *London,* 1922

FINDLAY, A. The treasures of coal tar.
sm. 8vo. 151 pp. *London,* 1917

FLIGHT, W. S. Phenol-formaldehyde products in the electrical industry. The effect of heat on the electric strength of some commercial insulating materials. Machining ebonite, fibre, and other insulating materials [*anonymous*].
8vo. 72 pp. *Preston, n.d.*

GARCKE, E., and FELLS, J. M. Factory accounts, in principle and practice. 7th ed., revised, with a foreword by J. M. Fells. 8vo. 310 pp. *London,* 1923

GIBSON, A. H., *D.Sc., editor.* Hydro-electric engineering. vol. 2, Electrical. Contributors: W. A. Coates, F. E. Hill, S. Neville, and the editor.
la. 8vo. 321 pp. *London,* 1922

GLAZEBROOK, *Sir* R., *K.C.B., D.Sc.* A dictionary of applied physics. vol. 1, 2. 8vo. *London,* 1922
1, Mechanics—Engineering—Heat.
2, Electricity.

GOUDIE, W. J., *D.Sc.* Steam turbines. 2nd ed.
8vo. 822 pp. *London,* 1922

HALER, P. J., and STUART, A. H. A second course in engineering science.
sm. 8vo. 257 pp. *London,* 1922

HAWKINS, C. C. The dynamo: its theory, design and manufacture. 6th ed. vol. 1.
8vo. 638 pp. *London,* 1922
The earlier editions of this work are by C. C. Hawkins and F. Wallis.

INDIA: PUNJAB PUBLIC WORKS DEPARTMENT. The Sutlej River Hydro-Electric Scheme. By Bt. Lieut.-Col. B. C. Battye.
vol. A, 5–8. folio. *Lahore,* 1921–22

KEEN, R. Direction and position finding by wireless.
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KEINATH, G. Die Technik der elektrischen Messgeräte.
8vo. 455 pp. *München,* 1921

KEMP, P. Alternating current electrical engineering. [2nd ed.] 8vo. 526 pp. *London,* 1922

LANGMAN, H. R., and BALL, A. Electrical horology. A practical manual on the application of the principles and practice of electricity to horological instruments and machines for the measurement and transmission of time; with an account of the earliest electrically-driven clock mechanism.
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LONDON COUNTY COUNCIL. Reports on the manufacture of gauges and the training of munition workers in certain London technical institutions during the war. 8vo. 90 pp. *London,* 1921

MAIN, F. W. Electric cables.
sm. 8vo. 111 pp. *London,* 1922

MARSH, C. F., and DUNN, W. Manual of reinforced concrete. sm. 8vo. 520 pp. *London,* 1922

MARSHALL, C. W. Modern central stations.
sm. 8vo. 125 pp. *London,* 1921

MEARES, J. W., *C.I.E.* The law relating to electrical energy in India. 2nd ed., revised.
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8vo. 224 pp. *London,* 1922

MOTTELAY, P. F., *Ph.D.* Bibliographical history of electricity and magnetism, chronologically arranged. Researches into the domain of the early sciences, especially from the period of the revival of scholasticism, with biographical and other accounts of the most distinguished natural philosophers throughout the middle ages. With an introduction by the late Prof. S. P. Thompson, D.Sc., F.R.S., and a foreword by Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S.
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folio. 51 pp. *Melbourne,* 1920

OULTON, L., and WILSON, N. J. Practical testing of electrical machines. [2nd ed.]
sm. 8vo. 258 pp. *London,* 1921

PARR, G. D. A. Electrical engineering testing. A practical work on continuous and alternating currents for second and third year students and engineers. 4th ed. 8vo. 703 pp. *London,* 1922

POOLE, H. E. Switching and switchgear.
sm. 8vo. 127 pp. *London,* 1922.

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sm. 8vo. 760 pp. *London,* [1922]

PRICE, H. W., and DUFF, C. K. Papers on current transformers. [University of Toronto, School of Engineering Research, Bulletin No. 2, 1921.]
8vo. 65 pp. *Toronto,* 1921.

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sm. obl. 8vo. 21 diagrams. *London,* [1922]

ROGET, S. R. A first book of applied electricity.
sm. 8vo. 150 pp. *London,* 1921

SMITH, C. F. The testing of transformers and alternating current machines.
sm. 8vo. 102 pp. *London,* 1922

SPIEGELHALTER, E. K. Wireless valve receiver set. How to make it.
sm. 8vo. 79 pp. *London,* 1922

SUMMERS, A. L. Anthracite and the anthracite industry. sm. 8vo. 135 pp. *London,* [1922]

TAYLOR, W. T. Electric power systems.
sm. 8vo. 119 pp. *London,* 1922

—— High voltage power transformers.
sm. 8vo. 127 pp. *London,* 1922

THOMAS, H. Traité de télégraphie électrique. 2e éd.
la. 8vo. 1,224 pp. *Paris,* 1922

UNITED STATES. ARMY: SIGNAL CORPS. The principles underlying radio communication. 2nd ed. Radio communication pamphlet no. 40. Revised to May 24, 1921.
sm. 8vo. 619 pp. *Washington*, 1922

VICTORIA, *State*. "Power" for Victorian industries A complete account of the great electric power and fuel supply scheme authorised by the Premier (Mr. H. S. Lawson) and State Government of Victoria, and now being carried into effect by the Victorian Electricity Commissioners; etc. [Supplement to "The Industrial Australian and Mining Standard," 17th March, 1921.]
folio. 79 pp. *Melbourne*, 1921

WADDELL, J. A. L. Specifications and contracts. A series of lectures; including examples for practice in specification and contract writing, together with notes on the Law of Contracts.
8vo. 169 pp. *New York*, 1922

—— Two addresses to the engineering students of the University of Barcelona. Delivered April 19th and 21st, 1922.
8vo. 23 pp. [*New York*, 1922]

WALMSLEY, R. M., *D.Sc.* Electricity in the service of man. vol. 2, section iii, Technology of electricity.
8vo. 863 pp. *London*, 1921

WAR OFFICE. Signals Experimental Establishment. Technical report. September, 1922. [*In MS.*]
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WESTERN AUSTRALIA. Electricity supply stations of W.A., 1922. Compiled by A. F. Williamson.
obl. folio sheet. *Perth*, 1922

WHITE, H. G. Telephone erection and maintenance. 3rd ed. sm. 8vo. 151 pp. *London*, [1922]

WHITE, W. J. Questions and solutions in magnetism and electricity. Consisting of solutions to the questions set by the Board of Education and City and Guilds of London Institute in stage 1 of magnetism and electricity during the years 1907–1921. Solutions by W. J. W. [2nd ed.]
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WHYTE, A. G. The all-electric age.
8vo. 255 pp. *London*, 1922

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YATES, R. F., and PACENT, L. G. The complete radio book. Preface by A. A. C. Swinton, F.R.S.
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THE INSTITUTION OF ELECTRICAL ENGINEERS.

No. 38. MAY 1923. INSTITUTION NOTES. [ISSUED WITH No. 318 OF THE JOURNAL.

Annual General Meeting.

The 51st Annual General Meeting of the Institution (Corporate Members and Associates only) will be held on Thursday, 31st May, 1923, at 6 p.m.

Annual Conversazione.

The Annual Conversazione will be held at the Natural History Museum, South Kensington, by permission of the Trustees of the Museum, on Thursday, 28th June, 1923.

The Institution of Engineers (India).

The I.E.E. Premium, value £20 (see *Institution Notes*, No. 16, page 2, December 1919), has been awarded by the Council of the above Institution for the year ended 31st August, 1922, to Mr. A. Lennox Stanton for his paper on "Railway Electrification, with special reference to Indian Conditions."

Associate Membership Examination Results.

OCTOBER 1922, SUPPLEMENTARY LIST.*

Passed.

Plowman, A. S. (Sydney, Australia).

FEBRUARY 1923, ROYAL CORPS OF SIGNALS.

Passed.

Bennett, M. C., Lieutenant (Indian Army).
Boyd, L. C., Lieutenant (Royal Ulster Rifles).
Boyt, W. D., Lieutenant (Royal Garrison Artillery).
Crouch, C. H., Lieutenant (Royal Garrison Artillery).
Halliday, G. R., Lieutenant (Royal Garrison Artillery).
Hannah, A. J., Captain (Indian Army).
Helps, R. P. A., O.B.E., M.C., Captain (Lancashire Fusiliers).
Hemming, W. E. G., Lieutenant (Royal Garrison Artillery).
Holland, V. C., Lieutenant (Royal Artillery).
Howard-Smith, M. H., Captain (Indian Army).
Instrall, R. C., Lieutenant (Royal Garrison Artillery).
Neale, R. H., Captain (Lincolnshire Regiment).
Plummer, G. H., Lieutenant (Cameronians).
Stoddart, E., Lieutenant (Royal Garrison Artillery).
Thomas, W. F. P., Lieutenant (South Staffordshire Regiment).
Watkins, B. S., Lieutenant (Indian Army).

* See *Institution Notes*, No. 35, page 1, December 1922, and No. 37, page 9, March 1923.

International Consulting Committee for International Telephone Communication.

As a result of the suggestions made in the President's Inaugural Address delivered before the Institution on the 2nd November last, M. Paul Laffont, Sous-Secrétair de l'Administration des Postes et des Télégraphes for France, called a preliminary technical international conference to study and recommend what steps should be taken by the European Administrations to improve and consolidate international telephone traffic in Europe.

The meeting was held in Paris commencing on 12th March, 1923, and was presided over by Monsieur Dennery, Inspecteur-Général des Postes et des Télégraphes, and was attended by representatives from France, Belgium, Great Britain, Italy, Spain, and Switzerland. The deputation for Great Britain was headed by Major T. F. Purves, O.B.E., Engineer-in-Chief to the British Post Office, and the other nations were similarly strongly represented.

At this conference certain recommendations were decided upon and these will, in due course, be submitted to the various Administrations in Europe. In the meantime, it may be stated that the committee has emphasized, as of primary importance, the necessity of complete unity as regards principles and practical realization—under present conditions of the telephone art—as well as in all matters concerning material and technical and commercial operation.

Consequently the committee has recognized the necessity for forming a permanent international consulting commission for international telephone communications. The different countries of Europe will be represented on this Commission, the official title of which will be Comité Consultatif International des Communications Téléphoniques Internationales.

The continuity of the work of this Commission will be secured by the establishment of a permanent Secretariat in Paris, which will also be a centre for international technical information. Pending the constitution of the Comité Consultatif International, the preliminary technical Committee has decided that its President, M. Dennery, and its General Secretary, M. Valensi, shall fill provisionally the offices of President and of permanent Secretary of the Comité Consultatif International.

The preliminary technical Committee has indicated the guiding principles, from now onwards, for the construction of international lines, their maintenance and development.

The collaboration between nations created by this

preliminary Committee has permitted, moreover, the formulation of a programme for new routes of communication both by aerial lines and by cables which are immediately required and which should be completed in 1923 and 1924. Finally the Committee will prepare a decennial programme for European telephone trunk lines. The main outlines of the scheme have already been determined and it will be completed during the course of the year.

Informal Meetings.

The following Informal Meetings have been held:—

38TH INFORMAL MEETING (22ND JANUARY, 1923).

Chairman : Mr. A. B. Eason.
Subject of Discussion : "Insulators and Insulating Materials" (introduced by Mr. A. G. Warren).
Speakers : Messrs. E. W. Moss, C. C. Paterson, O.B.E., H. M. Sayers, W. E. Rogers, A. C. Warren, E. H. Rayner, W. S. Flight, A. Monkhouse, A. Rosen, A. Collins and P. Dunsheath.

39TH INFORMAL MEETING (5TH FEBRUARY, 1923).

Chairman : Mr. F. Pooley.
Subject of Discussion : "The Supply of Steady D.C. for Telephonic and other Purposes" (introduced by Mr. J. Coxon).
Speakers : Messrs. F. Reid, A. F. Harmer, W. E. Rogers, C. J. Ashton, R. J. Hines, H. J. Gregory, F. W. Adcock, H. Kingsbury, A. B. Eason, W. L. Wreford, J. R. Bedford, R. V. Hook, G. H. Elsden and F. Pooley.

40TH INFORMAL MEETING (19TH FEBRUARY, 1923).

Chairman : Mr. E. F. Hetherington.
Subject of Discussion : "Esprit de Corps" (introduced by Mr. F. Peake Sexton).
Speakers : Major G. H. Spittle, D.S.O., Messrs. W. E. Rogers, J. R. Bedford, F. Pooley, W. Lunn, E. F. Hetherington, A. G. Hilling, H. H. Long, J. Coxon, M. Whitgift and W. L. Wreford.

41ST INFORMAL MEETING (5TH MARCH, 1923).

Chairman : Mr. A. F. Harmer.
Subject of Discussion : "Control in Industry" (introduced by Mr. J. H. Parker).
Speakers : Messrs. W. Day, N. Wylde, H. W. Healey, W. E. Warrilow, W. E. Rogers, F. C. Knowles, W. J. Oswald, — Bing, G. J. D. Scott, A. G. Whyte and A. H. Bennett.

42ND INFORMAL MEETING (19TH MARCH, 1923).

Chairman : Mr. W. E. Warrilow.
Subject of Discussion : "The Need for Co-operation between Electrical Manufacturers and Contractors" (introduced by Messrs. H. T. Young and J. F. Caine).
Speakers : Messrs. E. E. Sharp, W. R. Rawlings, A. G. Beaver, W. Day, A. F. Harmer, W. E. Rogers, C. Peel, A. Windibank, E. C. Wansbrough, F. Gill, E. H. Marryat, A. Wise, G. J. D. Scott and Major H. Brown.

43RD INFORMAL MEETING (23RD APRIL, 1923).

Chairman : Mr. E. W. Moss.
Subject of Discussion : "Practical Broadcasting" (introduced by Mr. E. H. Shaughnessy, O.B.E.).
Speakers : Captain P. P. Eckersley, Messrs. J. Scott-Taggart, J. R. Bedford, W. L. Wreford, R. Grierson, G. D. Dewar, W. E. Rogers, P. R. Coursey, W. Day, E. G. Bedford, A. C. Warren, A. G. Lee, H. S. Pocock, E. F. Hetherington, W. E. Warrilow, W. H. Lawes, E. W. Moss and J. C. W. Reith.

National Illumination Committee of Great Britain.*

REPORT OF CHAIRMAN FOR YEAR 1922.

In February last (1922) the provisional Definitions of Photometric Terms and Units proposed by the British National Committee were published together with a prefatory note and have been officially adopted by the three constituent Societies. They also form the basis of a set of Photometric Definitions shortly to be issued by the British Engineering Standards Association as part of a comprehensive set of Electrical Engineering terms.

The Definitions in question, whilst agreeing with the decisions of the International Commission on Illumination held in Paris in 1921, go considerably further and are in some respects at variance with a set of Definitions approved in July, 1922, by the American Engineering Standards Committee. The occasion of a visit by Dr. Clayton Sharp to this country in December last was seized upon to discuss these Definitions with one so largely instrumental in the drafting of the American Definitions. Dr. Sharp kindly consented to attend a Meeting of the Nomenclature Sub-Committee, and as a result of this interchange of views, the Sub-Committee are now considering how the proposed Definitions can be amended so as to minimize the points of difference between this country and the United States.

A preliminary list of Symbols has also been prepared by the Nomenclature Sub-Committee and, after submission to the British Committee, these have been communicated to a number of interested Societies, publication being deferred until their criticisms, if any, have been considered.

Dr. Mailloux (U.S.A.) and Mr. K. Edgcumbe (Gt. Britain) were asked by the central office of the National Illumination Commission to prepare an English translation of the French official text of Terms and Definitions adopted in Paris in 1921. A Meeting was held in this country and the translation agreed upon. The text forms an Appendix to this Report.

At the 1921 Paris Meeting of the Commission an International Committee on Automobile Headlights

* See *Institution Notes*, No. 30, page 11, January 1922.

was appointed and Mr. K. Edgcumbe was subsequently nominated by the British National Committee as their Representative thereon. A fairly complete set of recommendations having been drawn up in the United States by a Committee under the Chairmanship of Dr. Clayton Sharp, the subject was discussed with that gentleman on the occasion of his visit to this country, and at a subsequent interview with Mr. Perrin of the Ministry of Transport the question was raised of how the British National Committee could best serve the interests of this country in connection with Automobile Headlights. It appeared that the most useful course would be to appoint a Sub-Committee to consider the recommendations which had already been published in other countries, with a view, if possible, of arriving at common agreement through the medium of the International Headlights Committee.

In view of the fact that a large and increasing part of the work of the British National Committee relates to standardization, it was decided, with the approval of the three constituent Societies, to ask the British Engineering Standards Association to form a sectional Committee on Illumination to which such matters could be referred. It is proposed that this Committee should deal solely with standardization or similar questions referred to it by the British National Committee, all international matters being dealt with by the National Committee as heretofore.

K. Edgcumbe.
Chairman.

January, 1923.

PHOTOMETRIC DEFINITIONS.

Official Translation of the French Text.

Luminous flux.—Is the rate of passage of radiant energy evaluated by reference to the luminous sensation produced by it.

Although luminous flux should be regarded, strictly, as the rate of passage of radiant energy as just defined, it can, nevertheless, be accepted as an entity for the purposes of practical photometry, since the velocity may be regarded as being constant under those conditions.

The unit of luminous flux is the lumen.—It is equal to the flux emitted in unit solid angle by a uniform point source of one international candle.

Illumination.—The illumination at a point of a surface is the density of the luminous flux at that point, or the quotient of the flux by the area of the surface when the latter is uniformly illuminated.

The practical unit of illumination is the lux.—It is the illumination of a surface one square metre in area, receiving a uniformly distributed flux of one lumen, or the illumination produced at the surface of a sphere having a radius of one metre by a uniform point source of one international candle situated at its centre.

In view of certain recognized usages, illumination may also be expressed in terms of the following units:—

Taking the centimetre as the unit of length, the unit of illumination is the lumen per square centimetre; it is known as the "phot." Taking the foot as the unit of length, the unit of illumination is the lumen per square foot; it is known as the "foot-candle."

$$1 \text{ foot-candle} = 10{\cdot}764 \text{ lux} = 1{\cdot}0764 \text{ milli-phot}$$

Luminous intensity (candle-power).—The luminous intensity (candle-power) of a point source in any direction is the luminous flux per unit solid angle emitted by that source in that direction. (The flux emanating from a source whose dimensions are negligible in comparison with the distance from which it is observed may be considered as coming from a point.)

The unit of luminous intensity (candle-power) is the International Candle, such as resulted from agreements effected between the three National Standardizing Laboratories of France, Great Britain and the United States, in 1909.*

This unit has been maintained since then by means of incandescent electric lamps in these laboratories which continue to be entrusted with its maintenance.

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INAUGURAL ADDRESS

By FRANK GILL, O.B.E., President.

(*Address delivered before* THE INSTITUTION, *2nd November*, 1922.)

THE INSTITUTION.

My first duty must be to express my thanks to the members of this great Institution for their confidence in placing me in this chair, in the past successfully occupied by many eminent men; and as representing, in some degree, electrical engineers who have devoted their energies to what may be termed the light side of the science, I thank you for your trust. I confess to a feeling, not so much of pride in taking this office, as of doubt whether one can properly fill the position. Fortunately, I have no responsibility for the election—that is yours—but on me devolves the duty of doing the utmost of which I am capable to serve the Institution. That by itself, however, is not enough; the President is merely the spear point or the tool face, and that which may be accomplished by the point depends largely on the body behind it. By itself it can do little. I know your President is always assured of the support and sympathy of your Council, but I ask more—it is necessary that the living interest and support of every member should be behind the Council in their labours on your behalf.

As you are aware, the Institution is in point of numbers now the largest engineering Society in the British Empire, the total membership at the commencement of this session being 10 461 and the increase during the past twelve months 867. The conditions of, and qualifications for, membership are not being eased in any way, but are rather being made more severe; membership is becoming more recognized as a qualification, and the Royal Charter gives an added dignity and prestige. I want to see, and do not hesitate to call for, ungrudging service to the Institution from all its members, certain that if each will actively realize that the Institution is *his* Institution, its powers of, and opportunities for, useful service to mankind will be greatly enlarged. One of the grandest things about the engineering profession is its splendid tradition of service regardless of the cost to the server, fitly illustrated by the death of those to whose immortal memory the panels in the hall of this building stand, reminding all who enter of the simple road to greatness—Whosoever will be chief among you let him be your servant.

TECHNICAL EDUCATION.

As one illustration of service, the new Technical Education Scheme may be mentioned. You are aware from the Council's Report last May that the Board of Education has sought the assistance of the Institution in its management of technical education in England and Wales; accordingly, a joint Committee, on which the Board of Education and this Institution are equally represented, will be responsible for the curriculum in Electrical Engineering at such schools as elect to join in the scheme, for certifying as to the satisfactory nature of the schools and for the final examinations; and the certificates and diplomas issued to successful candidates will be signed on behalf of the Institution, the Board of Education, and the school. Many of our members feel strongly on the question of Education, and some have criticized the existing state of affairs in writings and verbally; now is their opportunity. Apart from service on the joint Committee, cases will certainly arise where they can help by showing interest in those schools which adopt the scheme, by gifts of apparatus and plant, by facilitating visits of students to works, by finding work for the students, and by criticism of the course of training, so as to make it really adapted for turning out men best equipped for their work in the world.

I want to make a special appeal also of a somewhat similar nature for interest in the work of the schools. It is tremendously important that, during their course of study, students should get first-hand acquaintance with actual commercial conditions, both as regards the conditions of work and acquaintance with the workers. So we find that universities and colleges endeavour to get temporary practical work for their students during vacations or at other times. It seems to me that managers (it is becoming an anachronism to speak of "employers") ought to feel it a duty to make temporary vacancies for such students, realizing that as hereinafter they will require adequately trained men from the schools, so in the meantime they also must do their share in the educational scheme by providing facilities impossible to the schools but possible to industry. As the time for premium pupils has, or ought to have,

passed away, so the time for hesitation in taking in such men for short periods ought also to pass away. Let the managers regard the students as possible future workers, and demand from them qualifications for apprehending what they see. I make a very earnest appeal to all those members of the Institution who are in positions enabling them to influence either opinion or practice on this matter, to make a point of doing what they can to meet this need. We take great care in the selection and treatment of the raw material to be worked up; we do not always take sufficient pains in selecting and training the raw human personnel which is to be trusted with the working of the raw material.

With great diffidence may I also say a word to those in control of the schools. During my time I have had a considerable number of men direct from the universities and colleges, among them, I am glad to say, being some very brilliant engineers, and I do not recollect a single failure. Probably the method of selection in which great weight is attached to the opinion of the professor as to the character of the applicant, has had a good deal to do with the success experienced. But I do not remember an instance of a student being familiar with the economic aspect of engineering studies, nor of one who had any idea of how to tackle a problem of engineering economics. Yet that question of economics is the fundamental problem of the engineer; let him neglect it and, even though brilliant, he becomes something else, a physicist perhaps, a mechanician or a constructor, but not an engineer, who, it seems to me, must ever link together the progress of science with the minimum of human effort, that is, with the most economical manner of achieving what is desired. In the construction of plant how often it happens that, when the engineer has decided what plant shall be installed, the question as to whether the plant shall or shall not be profitable is also decided; for when the plant has been constructed to the engineer's designs, the management can only affect results by a margin, important no doubt, but the fact remains that the decision as to what plant shall be installed settles also many other items of expense, both for labour and material. I know that the time at the schools is very fully occupied, but I believe that this subject of engineering economics ought not to be left untouched.

Electrical Communication.

I have thought that the subject to which I could most usefully direct your attention is one relating to the art of Electrical Communication, and particularly, though not exclusively, to Telephony over Considerable Distances. I propose, therefore, briefly to review some of the recent advances in the telephone art which affect long-distance communication in Europe, or, as I prefer to call it, "through communication," because distance is not necessarily a feature, though often it is present.

If we consider primitive man, his first and immediate need is for food, then shelter and defence, then tools and clothes; but directly he has arrived at the state in which his own and his immediate neighbours' wants have been supplied, so far as their own exertions can supply them, the need for communication arises, and that even before the need for transportation. There is, however, no need to insist on any priority as between these two arts. They are so intimately connected that we may, without any violence to meaning, define communication as transportation of intelligence. Without communication man cannot know where to obtain such of his requirements as he himself is unable to satisfy; without it there is no use in his producing more than he requires for himself, since, in its absence, he cannot know whence arises a demand for his spare produce. While all this is true of primitive man, it has applied much more intensely since machinery came to the aid of production in the complicated system of trade which now serves the world. That which fifty years ago was regarded as a luxury to be enjoyed only by the few, is now a necessity to the many; to-day no nation stands alone or is sufficient for itself; more and more the interdependence of nations is being recognized; and more and more is it realized that no nation can be prosperous or afflicted without a result being felt by other nations. It were easy to illustrate this community of nations by taking the clothes we wear, the food we eat; but all this is well known to you. It is sufficient to say that to bring together the products of all the world to your doors is the work of communication and transportation, and that the efficiency of both is vital. Other things being equal, the nation best equipped with the means of production, communication and transportation, will enjoy a great advantage in the race for commercial supremacy, and perhaps also in the search after national well-being. It follows, therefore, that a great responsibility is laid on those to whom is entrusted the means of communication, or who control those means, whether Government department, public company or other agency, and particularly so because it is at last generally recognized that competition is not an aid to efficiency in this business. In return, therefore, for the grant of facilities to carry on its work, each grantee authority must ultimately recognize its duty to the public and, if it realizes this, dare not adopt either the selfish attitude of attempting to make as much profit as possible, or the passive attitude of merely supplying the service demanded by the public. To discharge its duty it must diligently and actively search out new means and facilities and also set about educating the public in regard to their need for communication. The authority is the custodian of the knowledge; it must teach the public what the public did not at first realize—that efficient communication is the life blood of commerce and of national and international understanding and amity—and without effective communication there would appear to be little chance of success for such projects as the League of Nations. It is by this campaign of education that the well-developed industries of the world have been stimulated, not by merely diligently serving the public demand. The railways have themselves created demands for traffic, the Press has done the same, so has every great and successful industry, and so must the telephone industry if it is not to fail in the performance of its duty.

The fact that so much of the means of electrical communication in Europe is under Government ownership, and under the present prevailing custom removed from the stimulus of profit-earning, makes it quite

possible that Governments may instruct their Telephone and Telegraph Departments that they do their duty when they diligently supply the public demands for service; and perhaps such a course is the more probable when the many other calls for expenditure experienced by Governments to-day are considered. But here a deliberate choice must be made: Is communication, and ever better communication, a necessity or not? If it is, then the passive attitude of merely satisfying public demands must be abandoned and an aggressive attitude take its place. It is not by a passive attitude that the great development in telephones has been built up in the United States, Canada, Denmark, Sweden and Norway, but rather by a resolute, purposeful and well-directed campaign of education of the public and of existing users. In the United States particularly there has for years been an educational campaign of a very high order, coupled with the construction of plant in advance, without which it is, of course, worse than useless to create demand. All this seems self-evident and trite, but two questions will test very quickly whether in fact this matter is quite so self-evident and obvious as it appears. These questions are: (1) Has telephony, during the 46 years it has been available, been of as much use to Europe as it might have been? (2) Have the organizations, Government and otherwise, been permitted to do what they have wished to do? The answer to both questions is most decidedly—No!

It will be noticed that above it was assumed, for the moment, that lack of profit-earning robbed a Government of the stimulus enjoyed by a public company; also that a Government department should not earn any more money than necessary to be self-supporting. It seems to me that both assumptions are fallacious. It is true, of course, that with a company the necessity for earning an adequate return on investment is a most rigorous stimulus, but, apart from profit-earning, a Government is subject to a powerful stimulus also. Only let it be realized that communication means something real—that it is a tool for the benefit of the nation, a necessity—and who is more vitally interested in obtaining the fullest possible utilization of that necessity than a Government? Who more vitally interested or more impelled to strain every nerve to teach the public the advantages of communication and extend the use of it by every means possible? The stimulus of profit-earning to produce development is small compared with the stimulus which comes to a public department as trustee for the nation.

But it seems also wrong to reason that a Government department should not earn something more than just enough merely to pay its way. It is undoubtedly healthy for the *esprit de corps* of any organization that its personnel should know that their organization is an efficient one, in which they can take a justifiable pride; and one of the ways of testing the efficiency of public concerns is to associate service with returns. With a staff comprising many persons, it is unhealthy that the idea should prevail that profit-earning is of no account. There is, however, more than the question of the effect on the staff, important though that be. Without a surplus of income over expenses there is no margin for unforeseen contingencies which must constantly arise in such a flexible business; service trials and research are likely to be adversely acted upon, and capital will be raised with greater difficulty. Further, there seems no reason why a Government should not include in the rentals a sum plainly intended to be a contribution towards revenue; it is difficult to see any reason why it is permissible, for the purpose of raising revenue, to tax, say, food but not telephones, or why it is proper to make a considerable surplus on postage, but not on telephones. It would seem that the correct course is for a Government, if it operates the telephones of a nation, to raise from them something towards the National Revenue, and to pay such a return on the capital invested in the business as to make certain its ability to raise whatever money may be required to extend the business.

Let us now pass on to consider some of the alterations in practice caused by recent developments in telephony as they affect long-distance or through communication.

Loading.—By this term is meant the deliberate addition of inductance to the circuit for the purpose of increasing the distance over which satisfactory speech is feasible. Such inductance may be in the form

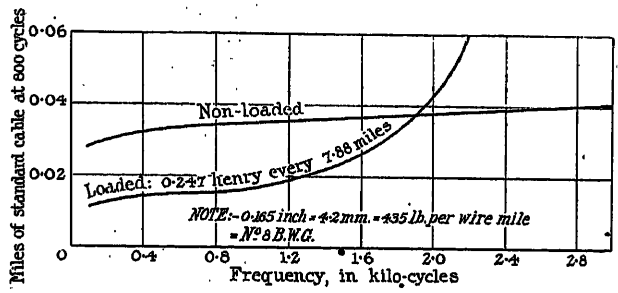


FIG 1.—Attenuation/frequency characteristic of 1 mile of 0·165 inch open wire line. Dry weather conditions assumed.

of evenly distributed inductance effected by wrapping the copper conductor with magnetic material, such as fine iron wire, or, and more commonly, may be in the form of lumped inductances obtained by inserting in series in the circuit at intervals coils having the required inductance and a minimum resistance. In was in 1887 that Oliver Heaviside pointed out that the addition of inductance by either of these methods—inductance being then thought harmful—would be beneficial to the transmission of speech.

Fig. 1 shows the loss for one mile of circuit at various frequencies in respect of open wire circuits weighing 435 lb. per mile (4·2 mm diam.) both for non-loaded and for circuits loaded with 0·247 henry every 7·88 miles (12·7 km); the computations are made for the steady state, that is, when the temporary effect of transients has passed off. From these curves we may see that the effect of loading has been threefold: (1) The attenuation has decreased taking 800 cycles for example, from 0·035 to 0·016 mile of standard cable, a reduction in loss, that is an improvement in volume of speech, of 54 per cent. (2) Between about 400 and 2 000 cycles the curve of loss has a greater slope for the loaded line, indicating that the various frequencies necessary to

transmit satisfactory speech are less uniformly transmitted, thus increasing the frequency distortion and so degrading somewhat the quality, which was of a very high order on the non-loaded line. (3) At about 2 000 cycles the attenuation of the loaded line undergoes a decided increase, termed the cut off, so that high frequencies are extinguished. In addition to these three effects, the speed of the circuit has fallen from 180 000 miles per second for the unloaded line to 55 000 miles per second for the loaded line.

Fig. 2 shows the results of loading a circuit weighing 20·6 lb. per mile in dry-core cable with three different types of coil, each at a spacing of 6 000 feet (1 829 m). From this we notice four results: (1) The 800-cycle attenuation has fallen from 0·94 to 0·30 (taking the middle loaded curve as an example), a reduction of 68 per cent in the loss, a greater reduction than was obtained in the case of open wire. (2) Between 200 and 2 000 cycles the loaded curve is approximately horizontal, indicating that all frequencies between those

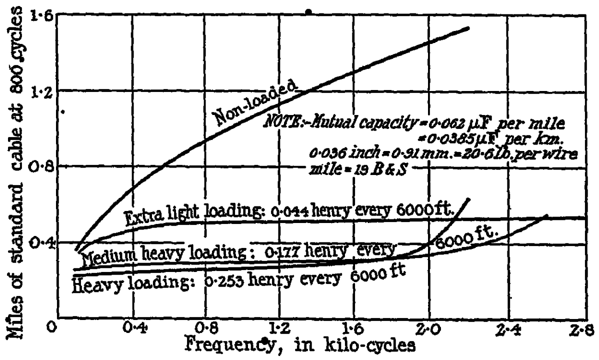


FIG. 2.—Attenuation/frequency characteristic of 1 mile of 0·036 in. cable circuit.

limits are almost equally transmitted, so that the frequency distortion, previously rather high, is made less, while the non-loaded curve has a pronounced slope; for example, the loss at 2 000 cycles is 1·45, that is, 56 per cent greater than at 800 cycles. (3) There is the same cut-off effect as was noticed on open wire lines when loaded. (4) The frequency of the cut-off point also falls as the loading increases. An additional effect is that the speed of the circuit decreases as the loading increases.

Figs. 3 and 4 show the effect of loading on the cut-off frequency and upon the velocity of the cable circuits referred to in Fig. 2.

It is seen, therefore, that the addition of inductance to circuits, whether open wire or cable, affords a means of greatly extending the distance to which speech is possible, and of reducing the copper required to transmit speech over such distances as were previously feasible. But it is also seen that, while loading reduces frequency distortion on the cable circuit, it increases this form of distortion on the open wire circuit; also that, by increasing the voltage in the circuit, it augments cross-talk; and it reduces the speed of propagation in the circuit.

So far as open lines are concerned, the reactions on the general plant caused by loading are that a higher class of construction, including transposition, and maintenance is required to avoid cross-talk and to keep up the insulation, for loaded lines are much more susceptible to reduction in transmission efficiency due to lowered insulation than are non-loaded lines. With poor main-

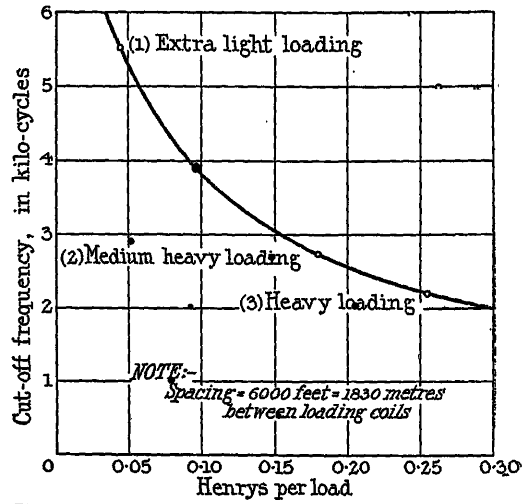


FIG. 3.—Effect of loading upon cut-off frequency.

tenance it may well be that the number of days in the year during which the improvement due to loading is gained is not sufficient to pay for the cost of loading.

This condition of constantly maintained high insulation applies also to loaded cable lines, but, high insulation being comparatively easy to achieve in cables, little

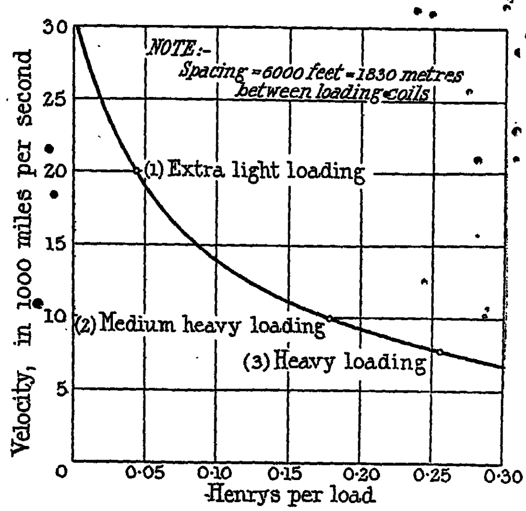


FIG. 4.—Effect of loading upon velocity of propagation.

reaction is caused by this. The increased cross-talk caused by loading has, however, caused real difficulty, which has been overcome by great advances in the cable art, not only as regards the construction of long-distance cable in the factory, but also as regards the jointing of the wires in the field, both these being intended to secure such freedom from unbalance

between circuits as will obviate cross-talk. It must further be noted that here, as in many of the latest developments, the effect of variables is not necessarily local; that is to say, a defect in one place may be felt a long way off in a section where no defect exists. There was also at one time, but this does not now occur so often, a necessity for great care to guard loading coils from becoming magnetized; this has been avoided in cable loading-coils by the use of compressed magnetic dust for the cores.

Repeaters.—Although the telephone repeater has been in service since 1905, it is only since 1914 that the thermionic repeater (which followed the introduction of the grid or third element by de Forest into the two-element thermionic valve of Fleming) has been employed, and the great impetus to its use has been given only during the last five years or so. The fact that a three-electrode vacuum tube acts as an amplifier of speech currents has led to an idea that a telephone repeater begins and ends in a device which relays the received current very much as does an electromagnetic relay; but the telephone repeater has many important conditions besides the amplifying one, and the fact that the reactions on telephone practice, due to the advent of the practical telephone repeater, have been and will be of very special importance makes it worth while to devote some little time to their consideration.

First let us look at the general types and their places in the system. There are, so far, three general types. First, the repeater which operates in two directions by means of a single amplifying unit, the so-called 21 type repeater; this must be placed at or near the centre point of the line because the impedances of the lines on each side of the repeater act as balances to each other, and, if they are not equal, the unbalance will cause circulating currents round the repeater, with the result that sustained oscillations will be set up and the repeater will "sing." Up to the present, this type cannot be used in tandem. consequently its use is limited. It may be applied either to open wire or to cable circuits. Second, there is the repeater which operates in two directions by means of two unidirectional amplifying units, the so-called 22 type repeater. With this type there is much greater freedom in locating the repeater, because the balance is not between the two impedances offered by the lines on each side of the repeater, but between the impedance of one line and that of a network made to simulate the line impedance, and the precision with which the network does simulate its associated line at all speech frequencies governs the degree of amplification or gain which may be taken from the repeater. If the balance is not held, circulating currents will cause the repeater to sing. Repeaters of this type are applicable to open wire and to cable circuits. They may be, and are regularly, placed in tandem, and as many as 23 have been used in tandem in regular service on a single conversation. This fact illustrates that the speech currents are transmitted with sufficient accuracy, as, otherwise, cumulative distortion would quickly cause degradation of articulation to an intolerable extent. Third, there is the repeater which operates in one direction only, the speech currents in the other direction being provided for by an independent circuit, the so-called 4-wire circuit, in which the currents from, say, East to West are taken by one circuit of two wires, with its unidirectional repeaters in tandem, and the speech currents in the other direction (from West to East) are taken by another circuit of two wires, also furnished with its unidirectional repeaters. Obviously, if a special 4-wire line were set up from subscriber A to subscriber B in which the circuit started with A's transmitter and terminated with B's receiver, and the circuit in the other direction were similarly treated, there could not be any circulating currents at

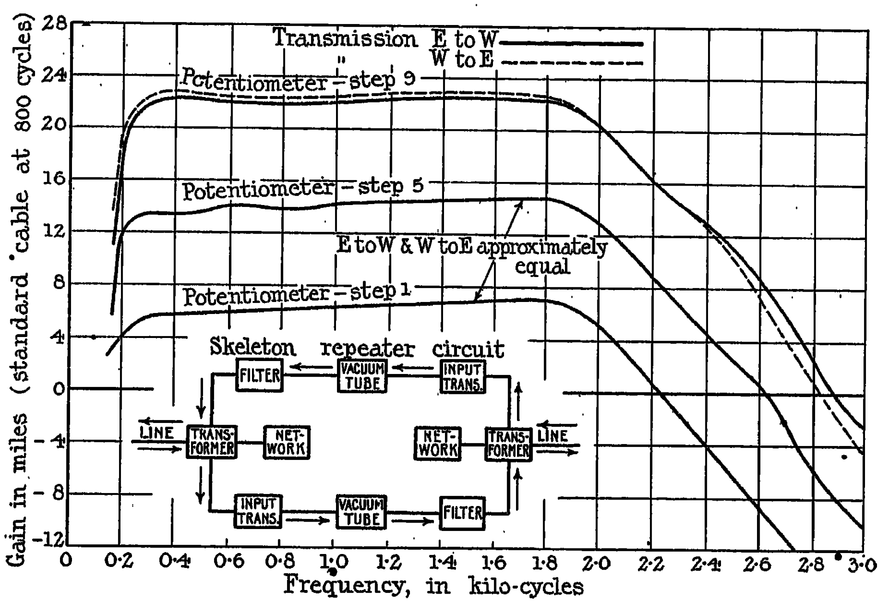


FIG. 5.—Gain/frequency curves of 22-type repeater.

all. Commercially, however, this is not possible, and it is necessary to use the regular 2-wire local system, so that only the long line portion of the circuit can be of the 4-wire type. With this type of repeater the circulating currents have to travel a long distance, which gives rise to great attenuation, before they can get back to their starting point for re-amplification, that, is, singing, and so a much greater gain can be taken from 4-wire repeaters than from 21 or 22 types, before the singing condition is approached. While the 4-wire type can be employed on either open or cable circuits, the fact that it required four wires makes it economically more suited to cable circuits; and since the gains obtainable are high (they can be made so high as to render the line loss zero between the terminals of the 4-wire section, which cannot be achieved by any other type) it is economically possible to employ this type of circuit in cable for distances up to 1 000 miles—perhaps further—and so it is pre-eminently suited for groups of long-distance lines carrying heavy traffic.

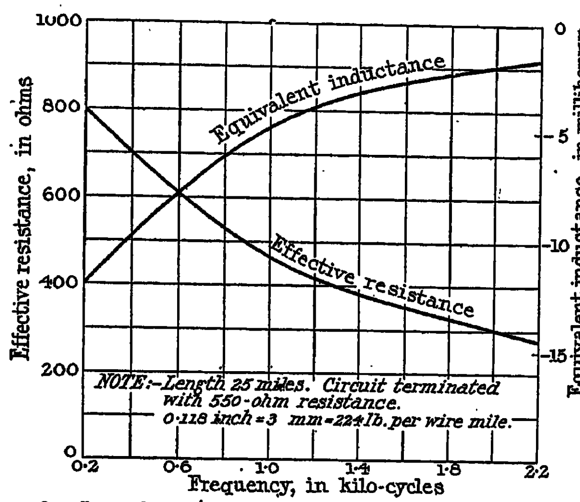


FIG. 6.—Impedance/frequency curve of 0·118 in. open wire non-loaded line.

Whichever repeaters are employed in any line they must, of course, be located at the right positions determined by engineering considerations alone and not by political ones. It might, for example, be correct for a line to run through Switzerland with no repeater on it at all in that country, or for a line to run through Limburg on which there would be a repeater in Holland, but no appreciable length of line in that State. In any such case the networks at the repeater in one country must conform to the lines situated in other countries.

The fact that telephone repeaters must be employed in tandem renders their requirements very severe. Fig. 5 illustrates the gains obtained from a repeater of 22 type, designed for a loaded cable circuit, taken at random and connected to an artificial line, the control of the gain being by a potentiometer with fixed steps. The top curve shows the gains from the two repeaters in the two directions, East and West, for speech frequencies when the two potentiometers were set on the same step, the ninth. The gain shown in the curve is approximately 22 miles, an energy amplification of 121 times. Of course it will be realized that this only shows what amplification the repeater can give; in practice, one would not expect such gains when connected to real lines. It will be seen how closely alike are the gains in each direction; that is, the speech currents are amplified in either direction with very nearly identical gains. When the potentiometers were set on the fifth step the gains were reduced, but the curves of the gain in each direction were practically indistinguishable, and the same held good when a still lower gain was taken by putting the potentiometer on the first step.

It will be noticed that these results were obtained, not by any careful and fractional adjustment, but merely by setting the two potentiometers on similar steps; and it will also be seen that the variation in gain produced by one step is approximately 2 standard miles. The small inset diagram indicates some of the pieces of apparatus involved, all of which have to play their part in the gain at speech frequencies, viz. input transformer, vacuum tube, output transformer, filter, and three-winding transformer in each repeating

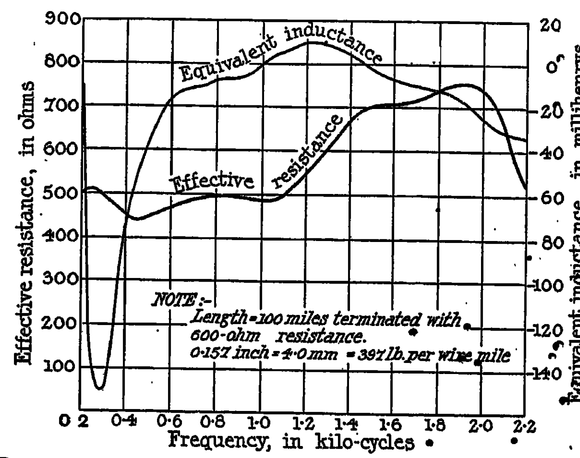


FIG. 7.—Impedance/frequency curve of 0·157 in. non-loaded open wire side circuit.

unit. The diagram does not show the potentiometers which are placed before the input transformers. It will be realized that the gain given out by the repeater must, of course, be adjusted to, and suitable for, the type of line with which it is to be used; also that a repeater is not a universal article which can be attached to any line regardless of its make up.

When, in actual service, repeaters are associated with lines, several reactions occur which very largely modify previous practice. As before stated, the line is balanced by an impedance network which simulates the line, but in order to keep these networks practicable it is necessary that the lines shall be as free as possible from irregularities, otherwise the networks would be very expensive and perhaps impossible. Fig. 6 shows impedance/frequency curves for an open wire line 41 km (25·5 miles) long of copper wires having a diameter of 3 mm (0·118 in.). This is an excellent example and so regular that there is no difficulty in providing a network which closely simulates the line; consequently, satisfactory repeater gains can be obtained. The

indicated results were found at the first trial and without any clearing up. Fig. 7, however, shows similar curves for a line that was regarded as a first-class one until tests were made on it prior to using a repeater. It is seen that its impedance curves are very irregular, so that in its then state it was quite impossible to employ a repeater. Fig. 8 shows a cable circuit 34 miles (54·7 km) long, from which, for some unknown reason, the seventh loading coil, about 17 miles (27·4 km) distant from the place of this test, had been removed. The impedance/frequency curves very plainly show how, by this removal, the line is thrown out of balance with the network, and one can thus see that the removal of the coil would at once render useless the line of which it forms a part. The removal of a loading coil is a noticeable matter, but the want of uniformity introduced by several portions of a line having different constants, such as non-uniformity caused by the haphazard joining up of lines not constructed with a view to the rigid uniformity required for repeatered lines, acts in the same fashion.

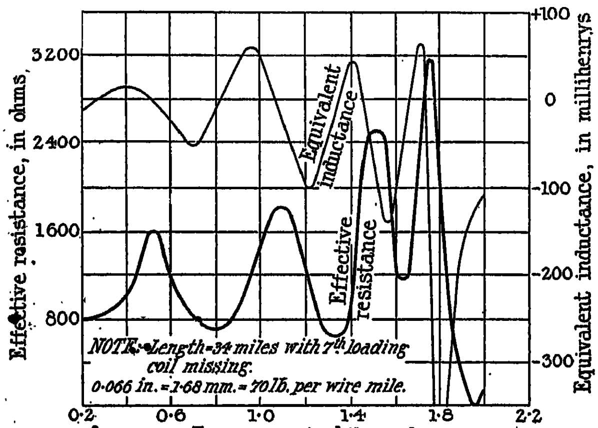


Fig. 8.—Impedance/frequency curve of 0·066 in. lightly-loaded cable circuit.

Fig. 9 shows impedance/frequency curves for a phantom loaded cable circuit 39 km (24 miles) long. It will be remembered that a phantom circuit is one which is obtained by superimposing the phantom on two circuits each composed of two physical wires, and it is not an easy matter to obtain a low unbalanced condition between the various capacities which make up such a circuit. In this figure are shown the curves for the line and for a theoretically uniform line, and it will be seen that the actual line does closely approximate to the theoretically perfect line.

Let us now see what is the overall result in transmission when employing a long line in which copper and repeaters both contribute to the effective transmission of speech—what, in fact, is the transmission afforded over the whole system. In Fig. 10 are shown frequency/attenuation curves for a non-loaded open copper wire line 3 400 miles (5 472 km) long. The curves reproduced are: (A) actual measurements on the line when using repeaters of a type designed for and suited to the line; (B) computations based on using imaginary repeaters giving uniform gains at all frequencies; (C) actual measurements when using repeaters suitable for other types of line but unsuited to this one. The line included 12 repeaters in tandem and the results are somewhat remarkable. They show (curve A) that the specially designed repeater in conjunction with the suitable line gives a fairly uniform overall loss, approximately 10 standard miles, between the frequencies of 400 and 1 800. On the other hand, curve B shows that the theoretical uniform-gain repeater if used would be very unsatisfactory, in that it would give a frequency/gain characteristic of a very undesirable kind and one which would greatly increase the frequency distortion. Lastly, curve C shows that a repeater suited to the character of one line, if used with another line to which it is unsuited, may give overall transmission of a highly unsatisfactory nature.

Since it is not yet practicable to transmit all frequencies equally, it is evident that some sort of a compromise must be made; and if a line is composed of several sections, on each of which a different compromise has been made, the final through result may be less satisfactory than need be, solely because of the fact that the compromises contain no unity of treatment. When repeaters are in operation, they must maintain

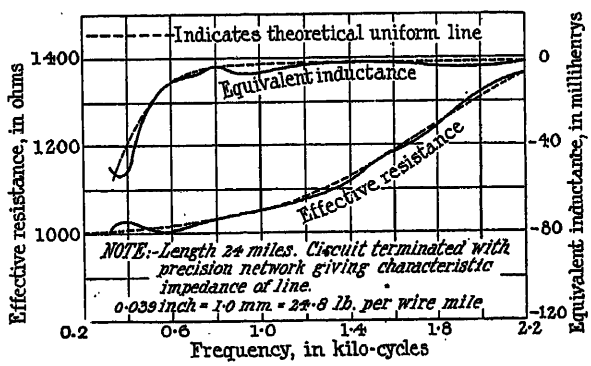


Fig. 9.—Impedance/frequency curve of 0·039 in. phantom cable circuit. Medium heavily-loaded cable.

constant the gains to be given out or there will be serious effect on the speech. If we assume a 4-wire circuit between Rotterdam and Milan, 500 miles (810 km) long and having five repeaters in it, operating at gains of 23, 30, 30, 30 and 23 standard miles (S.M.) respectively, say an average of 27·2 each, we need only consider what will happen if the gains fall off, since the gains will originally have been set to be as high as safely allowable. Assume, then, that the line without repeaters has a net equivalent of 148 S.M. from which we deduct the repeater gains, $5 \times 27 \cdot 2 = 136$, leaving the net loss = 12 S.M. Now suppose the gain at each repeater station for any reason at all falls off by 2 per cent; this will represent 0·54 S.M. each, or 2·7 S.M. for the five stations, and the net result will then be increased from 12 to 14·7 S.M., an increase of 23 per cent in the loss in the line. Should the gain on each repeater fall by 7·5 per cent the total additional loss will be 10·1 S.M., and the final net loss will be increased from 12 to 22·1 S.M.—an increase of 84·5 per cent. In this case the loss would be so great that probably the line would

become unworkable. I have chosen these examples to show the importance of uniformity of construction, uniformity of maintenance, and uniformity of operation; it will be seen afterwards what is their particular application. The examples are rather understated than exaggerated; it would have been quite reasonable to have taken a case with 20 repeater stations in tandem, and, furthermore, the gain given by a repeater would not in fact be one definite figure for all frequencies.

Fortunately, the design of repeaters has been carried far enough, so that, if correct design is employed and if certain regulations for operating routine and maintenance are followed, the gains can be held steadily; but among those routines are tests which determine when the useful life of an amplifying element, a vacuum tube, has ceased, and the required constancy in gain can only be held if all repeater stations are operating to the same routine. If the line is an aerial one and subject to considerable changes in temperature the resistance alters and another source of variation in overall transmission equivalent is introduced. If these changes are serious they can be compensated automatically; if not so serious they can be dealt with by operative routine. The lesson is, however, the same in either case, and, for the best results, those persons operating the various repeater stations must be operating to the same routine, employing the same technique and under the one control. Again, when breakdowns occur important circuits cannot stand out of order, but must immediately be temporarily re-routed to restore the service. Such alteration may affect the balance between the network and line at the repeater station, and this may have to be dealt with by altering the gain of one repeater (in which case alterations will probably be required at all other repeater stations along the line), or by changing networks. If it were possible to foresee all possible combinations and emergencies, it would doubtless be possible, though not economical, to establish routines covering all cases requiring attention; but obviously this is not possible, and the only commercial solution lies in unity of control of the line from beginning to end.

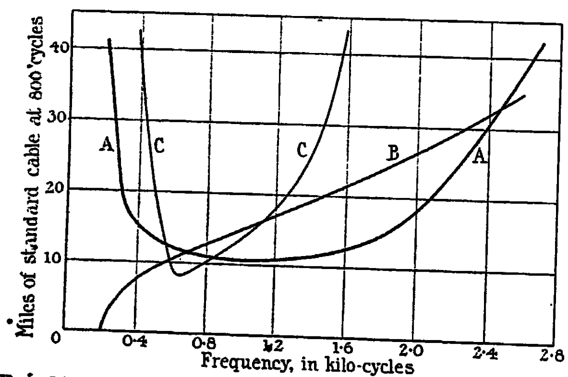


FIG. 10.—Attenuation/frequency characteristics of long open wire line.

It has been shown that the result of loading the circuit is reduced attenuation and somewhat impaired articulation in open wire circuits, and reduced attenuation and better articulation in cable circuits. Now that the use of repeaters has become possible, additional energy can be put into the line as required and the attenuation can be reduced by that means. It is therefore no longer necessary to sacrifice the quality which can be obtained on open wire circuits by loading them in order to reduce the attenuation—this reduction can be effected by repeaters. In cable circuits, however, it was shown that loading was necessary to reduce the frequency distortion. Consequently, long, heavy, open wire lines are not now loaded at all but are repeatered, resulting in improved articulation, and the increased speed of propagation avoids echo trouble, which only became insistent because of the more powerful effects derived from repeaters. With cable circuits, on the other hand, loading still obtains. It cannot be abandoned since it is necessary for the reduction of frequency distortion, but the tendency is towards lighter loading so as to raise the speed of the circuit, thus reducing the echo trouble which, because of the reduced speed and the great electrical length of loaded cable circuits, demands most careful consideration.

Carrier circuits.—In the search after increased capacity of telephone and telegraph circuits, there has recently been developed and put into commercial service the carrier system which has been added to the well-known methods of superimposing phantom telephone and compositing telegraph circuits. In this new method, carrier waves of different frequencies for each channel of communication are generated. If the channels are to be used for telephony such waves have a frequency above the audible limit. By means of band filters the desired range of frequency is permitted to pass into each channel, but only frequencies within that range; thus on a 4-channel telephone carrier circuit the frequencies might range in four or eight separate bands with outside limits of 4 000 to 27 000 cycles per second. Each carrier wave is modulated independently by the voice currents to be transmitted by that channel, and all the modulated carrier waves, or all of one of the side bands only, without the carrier waves, are transmitted over the line. Upon reaching the far end, the waves are filtered out, each into its proper channel according to the carrier frequency assigned to each channel, and are then demodulated, leaving the voice current free to be farther transmitted over an ordinary circuit. Because of the increased frequency of the carrier waves, greater attenuation occurs with them than with the voice waves, and carrier current repeaters must be equipped more frequently than voice current repeaters; also, for the same reason, carrier currents cannot be transmitted over ordinary loaded lines, which it will be remembered cut off at frequencies within the audible range. Hence, if loaded carrier circuits are required, they must be specially treated. Special treatment is also needed in the construction and maintenance of carrier lines and equipment, and because the equipment is expensive such lines must be of considerable length in order to be economical.

As an illustration of the advantages to be gained by using the latest development, the following may be quoted. On the New York–San Francisco line the circuits are of open wire from Harrisburgh to San Fran-

cisco, about 2 500 miles (4 050 km) direct distance apart. On four conductors on this route the loads carried are :—

2 physical telephone circuits,
1 phantom telephone circuit,
4 earthed telegraph circuits, and
a varying number of carrier telegraph circuits ranging from 6 to 20.

Two of the sections on this route in detail are :—

Between Chicago and Omaha.—450 miles (729 km) direct distance apart, four open wire conductors carry :

2 physical telephone circuits,
1 phantom telephone circuit,
4 earthed telegraph circuits which can be worked either 1 way or 2 way at will,
20 2-way carrier telegraph circuits.

27 total circuits on 4 wires.

This is shown in Fig. 11.

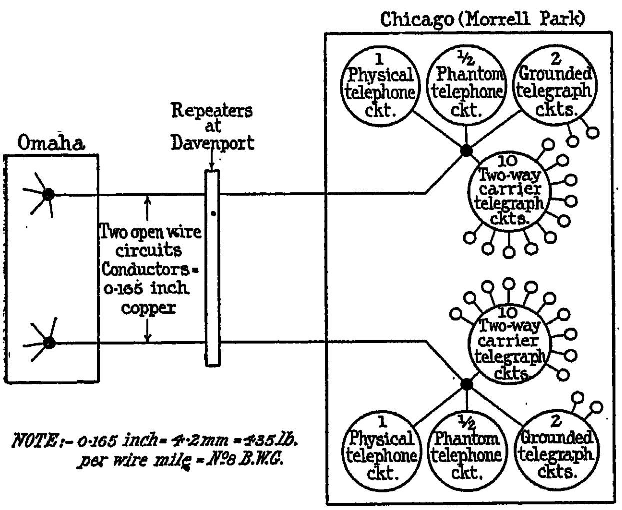


Fig. 11.—Diagram showing the load carried on the Chicago–Omaha line.

Between Chicago and Pittsburg.—450 miles (729 km) apart, eight open wire conductors carry :

4 physical telephone circuits,
4 halves of phantom telephone circuits (equivalent to 2 circuits),
8 earthed telegraph circuits which can be worked either 1 way or 2 way at will,
37 2-way carrier telegraph circuits.

51 total circuits on 8 wires.

From another route we take the following :

Between New York and Philadelphia.—90 miles (145 km) apart, two conductors in cable carry, though not by carrier circuits :

1 physical telephone circuit,
30 special signalling circuits.

31 total circuits on 2 wires.

From Chicago to Omaha or from Chicago to Pittsburg the direct distances are about the same as from Paris to Berlin, from Paris to Marseilles, or from London to Milan. From New York to Philadelphia is about the same distance as between London and Birmingham.

At present there are in actual service in the United States the following miles of carrier route and channel :

	Miles of Route	Miles of Channel
Carrier telephone	4 776	16 576
Carrier telegraph	10 919	78 870
Total	15 695	95 446

Cross-talk.—Applications such as have been described demand a much higher degree of refinement, in order to avoid cross-talk, than those which have previously obtained in the construction and maintenance of long-distance lines. To obviate that evil, it is necessary that at every point throughout the entire length telephone lines should have the two sides of the circuit equal in admittance to earth and equal in series impedance, and these must be equal over the range of voice frequencies. This is a very severe requirement, but very good approximations to the result required are being made.

Fig. 12 shows the effective resistance unbalances for a non-loaded open wire 4·2 mm (435 lb. per mile) phantom circuit in good condition, and also with an unbalanced leak between one wire and earth, 147 miles away from the point of test. Unbalanced conditions may obviously arise by such defects as faulty joints, incorrect transpositions, faulty insulation, and apparatus faulty in design or maintenance. Further, cross-talk as an effect of unbalance is accentuated by repeaters, since too much energy delivered into a line may produce an intolerable amount of cross-talk.

Interference.—A matter which is assuming more and more importance is that which in the communication art is termed "interference," meaning by that term the reactions which occur between weak-current communication circuits and heavy-current lighting, power and traction circuits.

The effects of these reactions to the communication engineer may be serious and fall under the heads of :—Noise; false signals; breakdown of the line; fire hazard; acoustic shock; electric shock.

Some consideration has already been given to the question of balancing the telephone circuits and, before looking at the same matter in regard to the power lines, perhaps it may be useful to give an idea of the relative trouble caused by different frequencies.

Fig. 13 shows the relative interfering effect of uniform currents at various single frequencies in a telephone receiver. The interfering effect is very unequal, and the importance of the wave shape in power circuits will be inferred from this curve.

On the power side, residual and balanced components of the power circuit voltages and currents may cause such trouble as to be beyond the ability of the communication engineer to cure. Every commercial three-phase system, for example, which has not been properly transposed is an unbalanced system, and any change in the separation of wires or height from the ground will affect the balance to earth, which generally is

of more importance than balance of load between phases. This unbalance can be much reduced by transposing the power lines. Again, even if well balanced during normal operation, power lines are invariably thrown badly out of balance by abnormal occurrences such as the opening or short-circuiting of the line; and sometimes the circuit and switching arrangements are such as needlessly cause unbalanced solution. Let the engineers of the two industries first get together, unfettered by any partisan tie, to seek the best methods of getting rid of the trouble, and after those best methods have been found, on the basis of the least total cost, then, and only then, let the question of settling the apportionment of cost as between the interests be taken up. The ordinary difficulties of a complex situation are frequently

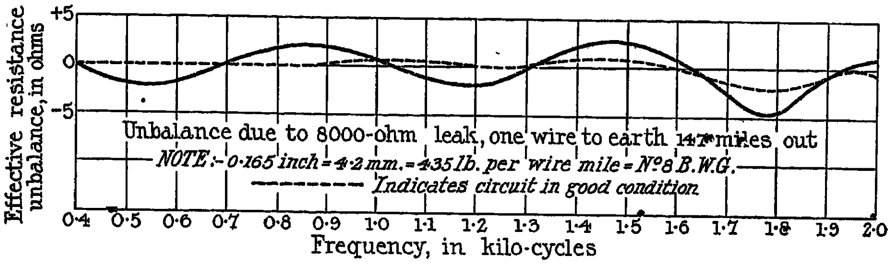


FIG. 12.—Effective resistance unbalance/frequency curve of 0·165 in. open wire non-loaded phantom circuit.

effects, not perhaps noticed by the power engineer, but very troublesome, if not worse, to the communication engineer.

Now it must be recognized that these industries—involving the telegraph, telephone and railway signalling systems as representative of the light-energy group, and the lighting, power, railway and tramway systems as representing the heavy group—are both of them necessary to the well-being of the world, and they must learn to live together harmoniously and to avoid or mitigate the otherwise serious reactions between their respective circuits. It must also be recognized that in grappling with this difficult problem there cannot be, and ought not to be, any claim by either side for priority of protection or preferential treatment. It is wrong for the heavy-current interest to say: Let the light-current industry take care of itself. And it is equally wrong for the light-current industry to say: The heavy-current business must be conducted in such a manner that we, with our existing arrangements, shall be undisturbed. There is only one sensible

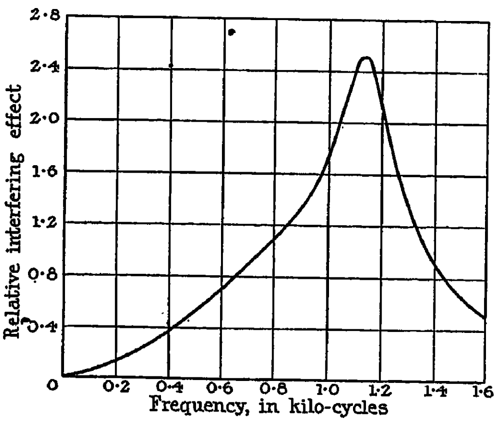


FIG. 13.—Relative interfering effect of single-frequency currents in a telephone receiver.

rendered more difficult of solution by an endeavour at the outset to fix responsibility for the interference.

Much has already been done by joint study to reduce interference, and in some cases, such as those of electrolysis, it has been found economical to the "heavy" industry to avoid certain defects in construction which were first brought to light by the complaining "light" industry. But in all cases the lesson is always being pressed home, that success is certain to come when each party makes a real endeavour to learn the other's problems and to appreciate the efforts made by him to solve them.

Heretofore a long-distance telephone line was a relatively simple structure consisting merely of a pair of copper wires, either open or in cable; this could be maintained comparatively easily in good order by independent maintenance units situated along the length of the line. But with repeaters and loading, that simple structure has vanished, the plant is more complicated, and the various parts are interdependent on each other. It is no longer possible to consider maintenance of each part solely as a sectional matter—what is done at one place may cause serious reactions at another, and the line as a whole must be considered.

We can now, therefore, obtain certain advantages in the construction of through lines, but only if we are willing to give the attention necessary to secure them. It is false to imagine that we can obtain the benefits of the present knowledge without taking the necessary steps to secure them. The benefits are:

Great increase in the distance over which communication can be given.

Great increase in the number of channels of communication, telephone and telegraph, which can be provided by one pair of wires.

Great increase in the number of circuits which can be placed in cable, numbers such that it would be impossible to find space for them if all circuits were to be open wires.

Greatly reduced annual cost of circuits and improvement in quality of speech.

Increased security of service by reason of circuits being in cable.

Increased speed of service by reason of greater number of circuits.

The principal points to which attention must be given in order to secure the above advantages are :—

Definite decision as to the work each line is to do, that is, planning in advance.

Definite standards of performance to be required of the complete line.

Unity of treatment of all transmission matter affecting the line over its full length.

Unity of treatment of all transmission matters affected by the connecting of the line to other lines, whether trunks or subscribers' lines.

Unity of maintenance control over complete length of the line.

Unity of control over repeater gains over the complete length of the line.

Unity of operating control over the whole length of the line.

Education of all sections of the telephone staff in transmission, maintenance and operating practices.

Without this education among all detail members of the staff it is impossible to obtain the benefits now available. It is not sufficient for a few engineers in any administration to be familiar with these matters; they must be made part of the general knowledge of all, and this is particularly true of education in matters affecting transmission which must, by some means or other, in the varying degree required, be made to permeate all classes of the staff who have to do with the transmission plant.

The telephone service has certain special features, as follows :—

(1) The unskilled public is an actual participant in a call; the matter is not merely handed over to a skilled operator, although the skilled operator also participates.

(2) It is essentially a through service, i.e. the whole circuit embracing the calling and the called persons' instruments and the complete line connecting them are simultaneously in use for each call; therefore, all parts of the circuit must be harmonious, although these parts may belong to and be operated by different owners.

(3) The operators at the various stages along the line have to co-operate with each other, and differences in the operators' technique will decrease the efficiency.

(4) It is a world service, for it is impossible to set any limits to the service, which must extend as the degree of technical knowledge permits.

Frequently in industry one cannot obtain an absolute standard, and recourse must be made to relative comparisons. It is so in telephony, and as I assume that I may take it for granted, at any rate by those who have studied the matter, that the telephone systems of the United States are in advance of those operating in Europe, it is worth while to see wherein lie the differences (altogether apart from ownership), and particularly the differences in organization, and to obtain some idea of the telephone system in the United States, which now has nearly two-thirds of the telephones installed throughout the whole world. In that country there are at present over 10 000 companies owning and operating over 14 000 000 telephone stations. That total number divides into two broad classes: those having some kind of connection with the Bell System, and those which have not. Again, the first class divides into those known as Bell-owned, and others as Bell-connecting with an independent ownership.

We may tabulate the telephone statistics of the United States thus :—

	No. of Companies	July 31st, 1922 No. of Stations	Per cent
Bell-owned companies ..	26	9 223 770	65·0
Bell-connecting companies (independent ownership)	9 289	4 520 725	31·8
Total Bell System ..	9 315	13 744 495	96·8
Non-Bell-connecting companies	879	452 597	3·2
Total	10 194	14 197 092	100·0

In his Presidental Address in 1905 Sir John Gavey referred to the growth of the Bell System as "absolutely startling." He said there had been an increase of 1 450 000 stations in 7 years—an average of 207 000 per year. But since then the increase in the Bell-owned companies has been an average of 410 000 per annum, or twice the number which startled Gavey.

Taking the population of the United States at 109 millions it will be seen that there is now one telephone station to every 7·7 persons, while in the year 1900 there was only one telephone station to every 56 persons. Since the beginning of the twentieth century, while the population has increased by 45 per cent and the volume of general business (judged by the best data available) by 100 per cent, the number of telephone stations has increased by over 900 per cent.

Again, if we judge progress by capital expenditure, we find that the investment of the Bell-owned companies, which was $180 700 000 in 1900, had increased by 267 per cent by 1911, and by 755 per cent by 1921, and then stood at a total of $1 543 865 545, say £346 000 000.

As a method of trying to give an impression of the telephone service in the United States, it may be said that from his telephone in that country a subscriber can reach out over more than 4 000 miles and can call practically any of the 13 700 000 stations referred to, situated in 70 000 cities, towns and villages; and the statistics show that the telephone communications in that country outnumber the postal communications by 50 per cent. It is agreed by those best qualified to judge that American industry on its present scale could not function without the telephone service as they know it there.

From these figures it will be seen that, while there are many telephones which are not part of the Bell System, the great majority (97 per cent) are part of that organization of companies, and, further, it may be stated that

with a few exceptions those companies which are not part of that system are, on the average, a collection of small concerns. In what follows, and generally in connection with the expression "telephony in the United States," the Bell System is referred to.

There are five outstanding features in the organization of the Bell System, and I think it may be said that these features are essential in any effective organization for telephony on an extended scale.

The five features are :—

(1) Local operating organizations, thus making for decentralization. These organizations, or companies, possess large measures of authority.

(2) A central administrative direction and control over the local organizations.

(3) A long-distance organization constructing and operating the long lines by which the local organizations effect intercommunication.

(4) Control of the manufacturing organization.

(5) A central organization for scientific research, development of apparatus and technique of construction, maintenance and operation.

In Europe, generally speaking, and considering the nations separately, we find :—

(1) An organization having a central authority with no separate local authorities.

(2) A series of administrative areas charged with the duty of maintaining the service under the central authority.

(3) No one department charged with the duty of through business.

(4) No control over manufacture.

When we consider Europe as a whole we find :—

(1) A number, about 40, of self-contained local operating organizations, each, in the majority of cases, conducting a local business and a through business within its area, also that part of the international through business which lies within its own borders.

(2) No organization controlling or co-ordinating the various local operating organizations, which yet have to function as a whole.

(3) No means of keeping the separate organizations in touch with each other, and no systematic means of adjusting differences in matters of daily practice.

(4) No organization of any kind which handles and cares for the through business as a whole.

(5) No common agreement as to manufacture.

(6) No common research, standard practice or technique of construction, maintenance and operation.

At the moment we are not concerned with the effect of this loose coupling upon the local business of each country, but little consideration is needed to appreciate its harmful effects upon the through business between countries, whether the length of line over which such business is conducted is great or small. There are in Europe large centres of population within such distances of, and in such commercial relationships to, each other that traffic would be forthcoming did adequate facilities but exist. There is no engineering difficulty, so far as distance is concerned, in constructing and operating lines at commercial rates to give satisfactory speech from any part to any other part of Europe, but at present the through business is meagre in quantity, slow and inefficient. Under the present conditions, practically the only way in which the nations can co-operate in these matters is that, when new lines are to be constructed between countries, there is co-operation and consultation between the representatives of the countries concerned, and occasionally there are international conferences. But these do not, and cannot, produce a unified system. All that they can do at the best is spasmodically and partially to compromise on a few outstanding differences in practice, which between whiles grow up unchecked, and to leave unsettled such large questions as cannot be agreed.

The settling of arrangements, and particularly the financial arrangements, for the construction of additional direct lines between contiguous countries constitutes an operation difficult enough; but when it is sought to construct lines between non-contiguous countries, in which cases they have to traverse countries not interested in the traffic desired by the terminal countries, the difficulties in the way of getting anything done are great indeed, and much praise is due to the energy and enterprise of those men who have succeeded in achieving the service now in operation.

Yet there is every indication that, given facilities, there is traffic waiting to be handled between the cities of Europe as between the cities of the United States. The opinion of some of those well qualified to judge is that the differences in language and customs do not, as they would at first sight appear to do, constitute a serious bar to international communication by telephony, and there are weighty reasons such as the present necessity of improving the relationship between nations, in addition to the normal commercial advantages, which render it safe to forecast sufficient through business to warrant the setting up of a competent organization with the plant necessary to handle the traffic.

There is, however, little likelihood of speedy and economical construction and operation of such lines as are necessary between, say, London and Stockholm, involving 3 or perhaps 5 intermediate non-interested countries, London and Kristiania involving perhaps 6 intermediate countries, or London and Petrograd involving 8 intermediate countries; and yet there is nothing fanciful in the idea of quick communication between such places. The direct distance between Brussels and Athens, or between Paris and Constantinople, is 1 300 miles—about the same distance as between New York and Omaha, or between Chicago and Salt Lake City, between which places calls can be made at any time. The direct distance over land between London and Bagdad is about the same as between New York and San Francisco, over which line conversations take place daily, while the direct distance over land between London and Delhi is about the direct distance from Key West in Florida to New York, thence to San Francisco and thence to Los Angeles, in California, over which distance calls can be made regularly. As a further encouragement, it may be said that the New York-Chicago cable, now in course of construction, will have a gross transmission equivalent so great that if a 435 lb. (4·2 mm) open wire circuit were constructed to that equivalent it might be 10 000

miles long, enough to connect Paris to the telephone system at Seattle in the North-West of the United States and leave enough to spare to take care of the cable across the Bering Strait. Of course, this illustration is uncommercial, but it serves to show that land distance is now no difficulty to telephony.

If we consider such business in the United States, we find that there are originated at New York over 4 000 000 long-distance calls per annum, and it will be remembered that in the United States many calls are made over lines of considerable length belonging to Europe. And yet there is no reason whatever why the service in Europe should not be extended in a somewhat similar fashion; from the fact of its denser population and less distant cities, Europe enjoys advantages over the United States, and these should make for much greater development of the through business than she now has.

It is not putting the matter too strongly to say that through-telephony in Europe under the present conditions can never be worth the name of a service, and that the alternatives are either for ever to be condemned

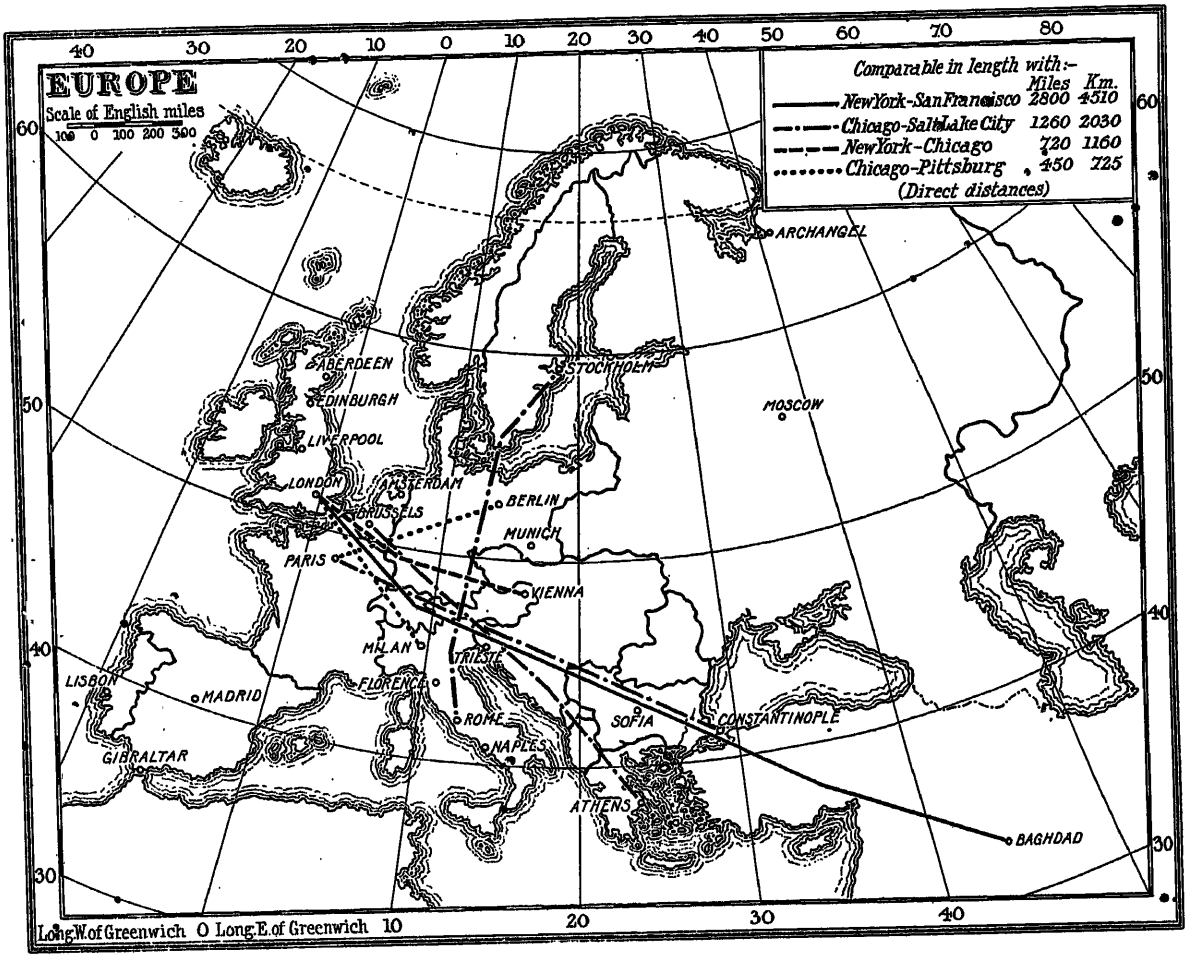


FIG. 14.

the local companies, and do not go over the long-distance lines. Similarly we find that Chicago and Philadelphia each originates something like 2 000 000 long-distance calls per annum, while such places as Boston, Cleveland and Pittsburg each originates about 500 000 long-distance calls per annum.

Fig. 14 is a map of Europe on which are shown a few of the long-distance circuits in the United States which are in regular daily commercial operation. It would have been easy to show a great many more, but this is not necessary in order to bring home the simple fact that there exists in that country a long-distance telephone service such as is not known in to an ineffective, inefficient state of affairs, or to find some plan, other than the present one, for dealing with the through business.

Analysing the conditions of through telephony in Europe as a whole, it is obvious that each nation, sovereign though it may be within its own territory, is really, from the telephone point of view, merely conducting a local business over an area which is not very great; it is also clear that no one local authority can operate its own through-business outside its own boundaries; although vitally interested, it must at its boundaries hand over the conduct of its business, in part, to someone else.

The through business must be handled as a complete unit if it is to be efficiently done; it cannot be done by independent units. The examples of recent improvements which I have referred to have been selected mainly because they illustrate the unity of treatment required by long lines. The correct course, therefore, appears obvious, viz. to depute a body to do for all European nations that which no one nation can do for itself. This is not a new departure; it is already practised by banks and railways in their clearing houses—no bank would now tolerate for a moment any attempt to effect for itself clearance of the various cheques presented to it daily, and consequently we find that the banks themselves have established their clearing house, which performs specialized functions for all banks, and thus expedites the work of all.

The corporate spheres assigned to any telephone authority may be determined by political, financial, legal or other considerations, and by reason of these spheres and considerations the authority is entitled to receive revenues and is obligated to pay the taxes and bills arising out of or payable in respect of those spheres. But these corporate spheres have, in reality, nothing whatever to do with the operating areas, which ought to be fixed solely with regard to obtaining the most efficient operating possible, and without any regard whatever to the corporate spheres. If the two differ, it is quite feasible for the operating authority to account as between any two or more corporate spheres without sacrificing any operating efficiency. Once the fact has been grasped that there is no reason whatever for the corporate spheres of influence and the operating areas to be identical, and that each requires quite separate consideration for its determination, there will be no real difficulty in arranging operating areas for efficiency and apart from corporate spheres.

With sectional, non-unified control over the various portions of the through business, it is not possible to design, construct and operate through-lines of communication in a manner capable of meeting the needs of the public. It has already been shown in what manner conditions in one part of the plant may react on conditions at another part, and how these parts may be distant from each other, so that in fact what is done in one country may render ineffective the efforts made in another country. It ought not to be necessary to labour this point, but perhaps an analogy may help. The through business is as much a unity as is military operation; we have seen the advantage gained by unity of command in warfare and no one would now advocate independent multi-commands such as were seen in 1914 and the early years of the war. If it was possible for the nations to agree on such unity of control for the purposes of war, it ought not to be beyond their powers to agree to a unity of control for the efficient working of the through-telephone business. It is not enough for the separate organizations to attempt to agree to a code of rules to which each shall subscribe—such an attempt would only be to court failure. The business is varying, flexible, and very much a living thing; it demands intelligent and prompt treatment of its many variations, it requires control from central points carrying with it the power to instruct persons at great distance in the routines and duties they are to perform, and such control can only be effected by a living authority always on duty.

Besides the engineering considerations which have been dealt with, there are weighty reasons connected with the matters of circuit lay-out business policy, rates and operating, about which much might be said, showing the impossibility of giving an adequate through service without unity of control, but this is not the place to deal with them.

It is easier to analyse the conditions and to state the fundamental requirements for efficiency, than it is to propound a scheme for an effective organization. Yet some effort at a solution must be attempted, even though it is unlikely that the first attempt will be successful. Any solution must find some method of satisfying the financial needs of the business as well as the technical requirements. At present it is difficult enough for the various administrations to obtain from their Governments the money required for the construction of such plant as is demanded by their own traffic, let alone for the fostering of traffic by the construction of lines not yet called for by public demand, and for the construction of lines between non-contiguous countries, which lines, although demanded, are not required by the natives of the intermediate countries through which they pass. In fact, in spite of the reality that Governments can borrow money at a cheaper rate than can public companies, it remains true that Governments do find difficulty in raising the capital necessary for the legitimate demands of telephone development.

The alternative suggestions which present themselves are:—

(1) To operate all the through business both within and between the various countries in Europe by a single long-lines company working under licences from the various Governments, taking the calls from the local originating organizations, and being entirely responsible for them until turned over to the local receiving organization.

Governments would put the long-lines company into a proper legal position, and make it plain that the company had the goodwill and support of the country, and they would co-operate with the company in the handling of the traffic. It might also be found desirable to turn over to the company, either on purchase or rental, certain lines and equipment already in existence for handling through traffic.

The advantages of this course would be that unified control could be achieved at once. The service would be on an ordinary commercial basis, and, if the fees were correct, sufficient money could be raised to construct all lines and equipment called for.

(2) The second alternative is for the various Governments to form what would in effect be a private company or Commission, of which the Governments only would be the stock-holders, to do the work described in the first alternative, and from each subscribing Government the Commission would derive its authority in that country. The Commission being supplied by funds, on some agreed plan of participation by each Government, would be the sole judges of the plant to

be constructed and operated, within the scope of the moneys put at its disposal, and it would assume the ordinary responsibilities of a board of directors of a public company, carrying out all the necessary functions and periodically reporting results to those who supply the capital. It might be that all plant constructed in any country should belong to that country, and that the capital to be provided by that country should be its proper share depending upon the plant within its own borders.

In addition, the Commission could hire facilities, where economical, from the local administrations in cases where it would not be economical for the Commission to construct its own lines. Such lines could be hired on a permanent or temporary basis. In the first case, they would be paid for at a proper rate per year; in the second case the local authority's lines might be made use of, and the compensation to be paid by the through-business Commission might be a proper portion of the fee paid by the public.

The above is the merest sketch of a scheme, but if it should find acceptance I am ready to put forward for consideration by the proper authorities a plan which I believe will be found to provide a basis on which the countries can be represented on equal terms and by which no unfair burden is placed on any country, and I believe that such a plan would result in better service and be self-supporting.

(3) The third alternative is frankly one of a temporizing nature, being intended only to cover a study of this difficult problem. It is that the various operating telephone authorities should form themselves into an association for the purpose of studying this and other matters. Such association might come about gradually if necessary, and regular meetings might be fixed for the purpose of studying a pre-arranged programme, which, apart from the larger question as to how the through business should be operated, might include the fixing of standards of measurement, performance and methods to be recommended to all, and to be enforceable on those who subscribe to the association.

If I may venture to make a definite suggestion, it is that the telephone authorities of Europe—including the United Kingdom—as telephone-operating authorities rather than as Government departments—should hold an early conference of all the telephone authorities, companies and municipalities, as well as Government departments, to study in detail this problem and endeavour to find a solution. I am convinced that unity of control over the through traffic must obtain in the end, but whether the through traffic is handled by one organization or by many, there are matters which urgently require agreement for the improvement of telephony as an efficient agent for service in Europe.

Almost entirely, what has been said is limited to through communication by telephony. This is not because there is nothing to be said regarding local service, but rather because it seemed better to try to focus attention on what at the moment is the greatest telephone problem in Europe, namely: How shall the through business be organized? Fortunately, the solution of this problem has never yet been seriously undertaken and, the whole matter being quite open, there are no standing decisions to be reconsidered. The engineering considerations make it plain that the communication which is possible, both technically and commercially, cannot be established under the present disconnected organization. As with a progressing organism, the time has come when the organization must, if it is to remain efficient, change from unicellular to multicellular, and the various cells must take up special functions rather than all functions; in that way only can the whole organization make progress.

One way of increasing goodwill among nations—especially necessary to be encouraged by all means possible at the present time—is by greater and ever greater intercommunication by all methods. In the telephone we have the most perfect means of communication of which we know, immediate and perfect human speech with all its tones and inflections, and the ability by interchange of conversation to remove misunderstandings. If only we will use it, not alone will it benefit the industry of the nation, but we shall be making a definite step towards reducing the international jealousies and fears and increasing the goodwill without which there cannot be peace on earth.

To those many friends for whose kindness in supplying data and discussing the subject here presented I am greatly indebted, I owe and tender my grateful thanks.

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By F. Tremain, Member.

(*Address delivered at* Bristol, *9th October*, 1922.)

In the first place I desire to express the honour which I feel in being elected Chairman of this Local Centre of the Institution, the success of which I have very much at heart. It is nearly 40 years since I was elected a Member and I am the happy possessor of a complete set of the *Journal*.

As I was unfortunately prevented from attending the Commemoration Meetings at which I was invited to speak, perhaps I may be allowed to enumerate some of the difficulties experienced by students in the early days soon after the passing of the Elementary Education Act. Especially in the provinces, there were very few science classes or laboratories and practically none for technical subjects, as the City and Guilds of London Institute could not for many years find qualified teachers. I, with another telegraphist and the local linesman, a trio of enthusiastic students, persuaded a science master to let us attend his elementary class after we ourselves had passed that stage, in order to take the advanced grade. Our plan was to use Silvanus P. Thompson's "Electricity and Magnetism," and study the small-print notes at the foot of each page, giving the mathematical proofs, etc., whilst the rest of the class took the ordinary course. We wrote up our notes and the teacher corrected them week by week. The plan proved to be not at all bad, as it formulated our work, which students working alone often find difficult. We took ordinary grade telegraphy with the same teacher, although he declared that we knew more about it than he did, but again with the aid of the City and Guilds syllabus he formulated our work, and we all three passed in both subjects. We then worked for and took the ordinary grade in Electric Lighting and Power, using Thompson's "Dynamo-Electric Machinery" as it appeared, I think, first in the *Electrical Review*. Finally, some of us passed in all the qualifying science subjects, and subsequently obtained Honours certificates in both Telegraphy and Electric Lighting and Power.

I was then appointed a registered teacher by the City and Guilds Institute, but although we had a most alluring circular printed, promising inspection of main lines, etc., not a single telegraph clerk would join the class. My partner and I then started inventing, and our first suggestion was a central-battery telephone signalling system, for which we took out provisional protection. On being submitted to the Engineer-in-Chief of the day it was, however, rejected as useless, it being then (in 1885) regarded as essential that signalling batteries should be at the subscriber's end and not at the exchange end of the line. This was the year of the Inventions Exhibition and I attended a class for teachers, conducted by Prof. Ayrton, at the City and Guilds Central Technical College adjoining the Exhibition. The procedure was a lecture in the morning, followed by laboratory work and demonstrations of the electrical exhibits. The teacher students included an Irish priest, a Whitworth Scholar, a Japanese and two or three others. We drove and compared an electric and a compressed-air tramcar, and tested an Immisch motor for efficiency at various speeds with a Prony brake and such measuring instruments as we could arrange for voltage, current, speed, etc. The supply was not very steady, and we had rather an exciting time getting simultaneous records of the various factors. At that time I was greatly interested in small electric motors for winding up the weights of Wheatstone telegraph apparatus and had already submitted a model to the Engineer-in-Chief of the Post Office. The Inventions Exhibition presented an opportunity for carrying out tests, and with Prof. Ayrton's permission we tested the efficiency of a little Cuttriss motor, the data obtained from which proved invaluable later. Subsequently the weights were abandoned, as were most of the train of wheels first in the Hughes printing instrument and afterwards in the Wheatstone apparatus, the motor driving the small remaining train of wheels direct. The Hughes as thus re-designed is still, I believe, the standard instrument in this country and on the Continent, wherever the instrument is largely used. Its final shape was, however, arrived at after many painstaking experiments.

These experiments were made two or three years after my first transfer to the Engineering Branch in 1887. There was at the time little or no development. Mr. Edward Graves was Engineer-in-Chief and Mr. W. H. Preece (afterwards Sir William Preece) was Electrician. These two gentlemen brought me on to their staff and I remained in London for 18 years. At the time of my appointment we numbered 10, including one draughtsman, but the Headquarters Staff now numbers, I believe, about 300. The annual expenditure on plant, extensions and maintenance was probably under £500 000, including the Stores and Factories Departments which are now separated from the Engineering Establishment. The Engineer-in-Chief of the British Post Office to-day is, I understand, responsible for an expenditure of £16 000 000 annually, and for the supervision and upkeep of plant approaching £100 000 000 in replacement value.

I wonder if our captains of industry realize the enormous potentialities of the well-equipped engineering students who come to them from the technical colleges. I have an uneasy feeling that they are

better utilized on the whole in other countries. Any one of them, if developed to the utmost, might prove a mine of wealth in the illimitable field of electrical knowledge, technically developed. Yet we hear of freshmen to the factory, with brain and hand well-trained, being put on machine tools. We want more engineering research and some industrial psychology if this country is to hold its own in the application of electricity to the service of man. If our industrialists in the electrical field would spend only 1 per cent of their net revenue in research work and propaganda I believe that they would be rewarded a thousandfold.

When I first joined the Engineering Branch of the Post Office I was stationed as examiner at the Department's new instrument factory at Holloway, and was one of three officers who tested and worked all telegraph and telephone apparatus after it had passed a mechanical examination before issue for service. Every instrument made or repaired in the factory, or made by an outside manufacturer, passed through our hands and was subjected to a test for correct resistance, insulation and capability to work at a figure of merit which provided a factor of safety under working conditions. We also tested some of the material before use, including the conductivity, etc., of silk- and cotton-covered wire used for winding apparatus. On the bobbins of the various relays, etc., there was little margin for variation of gauge and insulation. The smallest wire used was of 2 mils diameter with a thickness of silk covering ½ mil, making a total overall diameter of 3 mils. It may be interesting to detail the method of testing wire in those days. The wire was first gauged over and under the silk covering, and any doubtful reels were taken out. The method of checking the overall diameter was to wind on a small taper brass bobbin, on which 1 inch was carefully marked off from the cheek at the larger end, as many turns as covered the inch, examining the turns with a watchmaker's glass. The average diameter was thus ascertained, but before thus winding the wire it was carefully measured out into 10-ft. lengths and checked as regards resistance. The lengths so measured were placed in a box on the face of which was fitted a substantial plug-switch to which the ends of each length could be connected inside. Through a window in the box could be observed the scale of a special thermometer on which a few divisions were divided into tenths. The coils remained in this box for several hours to settle down. The measurements of resistance were made by a standard Wheatstone bridge and a Thomson mirror galvanometer. The object of the box and plug-switch was to protect the wires from draughts and the heat of the hand in changes during testing. After being tested for resistance the wire was measured for diameter, as explained above, then wound on a small copper cage and plunged into strong sulphuric acid for 5 minutes, afterwards passed into water, soda-water and fresh water in turn, dried by evaporation and weighed in a chemical balance. From the weight, the diameter and the thickness of the covering were deduced. The conductivity was generally found to be a point or two over 104 per cent of that of pure copper, according to Matthiessen's standard. All these various processes were carried out to a degree of accuracy well within one-tenth of 1 per cent, and as they were not likely to operate all the same way the result was considered to be accurate within 0·05 per cent. This will appear to be a very elaborate process for such small quantities of wire. It must be remembered, however, that in telegraph relays space is limited and the electromagnets have to change their polarity with great rapidity when working at, say, 400 words per minute. The purest iron core and the finest copper obtainable were therefore necessary if the relays were to respond to the specified figure of merit. It must also be remembered that in those days electrolytic copper was not so readily obtained commercially. I will mention one other instrument-factory experience, from which perhaps a more useful lesson may be drawn. There passed through the factory annually many thousands of instruments singly and assembled in sets, such as repeater boards, and amongst the former some hundreds of Wheatstone transmitters. One part of the gear is a rocking lever locked in its position (right or left) by a jockey roller. In this way is secured the reversal of current which, controlled by the punched slip, sends the signals to the line. When no slip is used, equally-spaced reversed currents are sent, and at 600 words per minute (the highest speed which has been obtained) these reversals take place at the rate of 240 per second, thus giving the note C below the stave in the treble clef. It can be imagined, therefore, that this lever and its jockey wheel performed a very important function. The lever was specified to be 17 mils at the root and 12 mils at the tip, for the purpose of checking which a template was provided. I had on one occasion a dozen of these on the bench and I remarked to my colleague that, as I had been gauging these for six months or more and had never found one wrong, I thought we might well trust this to the mechanical examiners who had previously checked the dimensions by a similar gauge. To my amazement, before I had examined the 12 instruments the upper end of one of the levers proved to be too thick for the gauge. The examining mechanic when called in was incredulous and thought my gauge must have been mutilated, but it was proved to his satisfaction that his gauge allowed too great a tolerance. I need hardly say that the check was not abandoned.

An interesting experiment in testing the strength of material for submarine cables illustrates the great care necessary in drafting specifications. I was engaged in a famous Thames-side cable factory supervising the manufacture of a submarine cable. The material before being presented to me was tested on receipt from the manufacturers by the cable makers' representatives, and on one occasion I was called to see a large quantity of galvanized iron sheathing-wire 0·280 inch in diameter which was said to be failing under a minimum breaking load of 3 500 lb. As there were six or eight barge loads in the delivery and the wire was said to be quite useless for any other purpose, the makers' representative was in some distress, and there was, of course, the danger of the sheathing process being held up for a considerable time if new

wire had to be manufactured. I inquired how it gauged and was told that it varied a little but was within the limits of 3 per cent laid down in the specification which, however, stipulated the minimum breaking strain for wire of the exact diameter. I agreed to accept a slightly lower breaking strain if the gauge were low, but within the specified limits, stipulating, however, that test-pieces from coils which gauged higher than the mean should carry a proportionately higher load before breaking. We carefully re-examined selected coils with quite satisfactory results and the whole consignment was passed. I need hardly say that the specification was amended for future jobs to provide for this contingency. The material was, as a matter of fact, excellent and quite up to specification.

The manufacture and laying of the first London–Birmingham cable provided me with an opportunity of testing air-space cable both at the factory and on the road. In this length (117 miles) over 570 tons of copper and 1 600 tons of lead were used. The cable consisted of 76 wires which in the first sections were laid up very loosely in four-wire quad formation so as to obtain a minimum specific inductive capacity between the diagonal wires. After some miles of the cable had been drawn into the pipes and jointed, a test was made which proved that there was considerable cross-talk between diagonal pairs of wires. By an elaborate system of crosses at test-pillars this cross-talk was eliminated, but the remainder of the cable was made up in 38 pairs and these pairs were given a variable lay so that no two pairs should be similar unless three pairs having a different lay intervened. On the completion of the cable between London and Leamington I was deputed to carry out a very exhaustive test, and to equip the cable completely. One half was to be equipped with various telegraph systems including duplex, quadruplex and Wheatstone automatic on loops and superimposed; and the other half with telephone sets. Although the cable was not intended for telephone purposes it was thought well to try what could be done. All the circuits so provided were worked simultaneously without difficulty, and the efficiency of the cable was thus proved. The test for capacity, resistance and telephone overhearing involved more than 6 000 recorded observations, and the equipment of the telegraph and telephone circuits involved the use of a very large quantity of apparatus, including 25 telephone circuits for listening-in at different parts of the cable and 12 such circuits for conversations which might be overheard by cross-talk.

As was mentioned in Sir William Noble's recent paper * and my remarks in the discussion thereon, I initiated the first loading experiments in this country early in 1901. The plant and apparatus used had to be improvised, and consisted amongst other things of 40 drums of 4-pair 20-lb. telephone distribution cable in ½-mile lengths; about 200 telephone induction coils used for loading; various telegraph switches for changing the coils; telephone transformers used as bridge leaks across a speaking pair and for phantoming in the ordinary way; and, of course, a Wheatstone bridge, Thomson reflecting galvanometer and, later, a secohmmeter. The cable enabled a loaded and unloaded circuit to be made up, identical as regards the factors K, R and L, and each 40 miles long with access to the circuits at every ½ mile. It was at these 160 points that the switches were required and each was a double-pole two-way switch. The most useful improvised loading coil was found to be the secondary winding of the 25/1 induction coil, the inductance of which was 70 mH. With two of these coils at each point, connected to the cable by switches so that either, neither, or two in parallel could be used, good results were obtained with two in parallel, giving, of course, 35 mH per point.

Bobbins of this size were next specially wound with two twisted pairs of 11-mil wire so as to get a greater range of inductance, viz. from 10 to 40 mH in each wire of a loop at each point; the coils having a total, in series, of 80 mH. With 37 of these coils inserted in 38½ miles of the distribution cable, excellent speech was obtained. This cable having served its purpose was dismantled and returned to the store. The coils were used for trials on the London–Leamington section of the Birmingham cable, and, as the cable had not been jointed through to Birmingham, a short completed section between Leamington and Warwick was next utilized as an experimental length. Test-pillars gave access to the cable at 2½-mile points at which tents were erected for coils, switches, etc., the cable being looped to and fro at the ends to make up a circuit of about 120 miles of 150-lb. conductor cable which could be extended at the ends to 140 miles. Adjustable inductances were made, giving a range of 5 to 62 mH without an iron core, and up to 160 mH with a core. This core consisted of 50 of the smallest, soft charcoal iron wire procurable, slightly stranded and covered with silk, and cut up into suitable lengths for the coils. Four of these laminated cores were used to obtain the maximum figure. The coil windings consisted of four sets of 1, 3 and 9 layers brought out to terminals and so wound and connected as to result in a capacity of 0·002 μF between the A and B halves when all in use. The variations of inductance were obtained by joining these windings in series or opposition, e.g. (A + B + C), or (A + B − C) or (B + C − A), etc., by means of switches, as well as by the insertion of 1 to 4 cores of iron. The coils were mounted in sets of 5 on a board with a protective cover and used in each tent. This proved to be an extremely useful arrangement and with it the best loading for all types of cable was ultimately determined experimentally. Cable circuits up to 200 miles in length were spoken through with aerial-line extensions of several hundred miles. The improvement due to loading, in terms of length, was found to be from 2½ to 3 to 1.

I will mention one more improvised arrangement involving the use of some 336 tumbler switches, fixed on a board in sets of 56 and arranged in 7 rows of 8. Each row of 8 was used to short-circuit or bring into use the inductances inserted in four pairs of wires. The 56 circuits were operated by means of a lath of wood and could be altered in a second or two, and as this was done at any one, or all, of six stations, the

* *Journal I.E.E.*, 1921, vol. 59, p. 389.

difference in the loaded and unloaded cable could be observed as often as desired. If alternate stations operated, the difference between 2½ and 5 mile loading could be observed. This also proved to be a perfectly satisfactory arrangement, as almost every conceivable combination could be arranged by varying the inductance values.

Based on the results obtained, standard loading coils were designed, but these have since been superseded by the hedgehog type of coil now being installed on the London–Bristol–Newport route and elsewhere. The cast-iron pots containing these coils weigh from ½ to 1¾ tons.

I shall only mention one other early difficulty necessitating improvization which may be interesting. Before the invention of the insulation-testing set known as the "Megger," I designed one with a horizontal pivoted galvanometer for use on the road. The trouble was to get the necessary voltage. On one occasion I cut about 10 cylindrical slices from each of 20 circular dry cells, and joining them in series found I could get a perfectly good test up to 5 000 or more megohms per mile. We therefore had 3 000 small dry cells made and fitted in boxes in sets of 50, brought out tappings to 4 terminals through safety resistances, and by using six of these boxes obtained the 400 volts necessary for a satisfactory test of dry-core cable during underground construction. Until the Megger came into general use these served the purpose quite well.

As an outcome of the experiments with the Birmingham cable, single-screened conductors were incorporated in the design of the cable, extending it through Warrington, Preston and Carlisle to Glasgow, with a branch from Warrington to Leeds and Newcastle-on-Tyne. Similar conductors were included in the West of England underground cable which extends from London through Bristol, Exeter and Penzance to Porthcurnow, for the Eastern Cable Company's service. The largest cable on this latter route, a sample of which is available here for inspection, is 3¾ inches in diameter and contains 32 pairs of wires and 72 screened conductors, the total weight of copper per mile being 9 tons, and of lead 20 tons. I believe that my estimate for this London–Porthcurnow cable, including pipework, drawing-in and jointing and testing equipment, was £328 000. The cable in the western sections of course became progressively smaller until at Land's End it was only about 1 inch in diameter. A comparison of this sample with one of the new London–Bristol cable now in course of completion illustrates the very great advance which has been made.

In the former cable 105 circuits (telephone and telegraph) are provided by means of 9 tons of copper per mile, apart from superimposing, while in the latter cable 308 pairs of wires are provided by means of 5½ tons of copper per mile, and the facilities for superimposing are much larger, as 154 circuits, apart from superimposing, would be provided with the 4-wire repeaters mentioned in Sir William Noble's paper. There are no screened conductors, such screening of telegraphs as is necessary to-day being provided by using one wire of a loop and earthing the other as a screen. Part of this cable will be extended to South Wales, and the cable and loading pots are, I observe, in position in the Bristol section.

The progress thus made in the 17 years since I left London for Newcastle-on-Tyne, on being appointed Superintending Engineer, is certainly very remarkable. Not only has loading increased the efficiency of telephone cables nearly three-fold, as I demonstrated, but by the use of thermionic valves in telephone repeaters a further four-fold improvement, at least, has been effected.

The improvement due to loading is perhaps comparable with that brought about in electric lighting by the substitution of metal for carbon filaments in lamps; but the further improvement brought about by the telephone repeater marks, I venture to say, a much greater relative advance in communication by telephone than that resulting from the use of the gas-filled lamp in electric lighting.

It appears to follow, therefore, that supply engineers have some leeway to make up, if they are to progress as much in their art as telephone engineers have in theirs. Until they obtain a 24-hour load for their generating stations the capital expended on their generating plant, substations, mains, networks and equipment, cannot possibly earn a full and adequate return so as to bring down the cost of energy to a competitive figure.

I was pleased recently to see in a Bristol newspaper a reference to a suggestion which I have been making to supply engineers for several years. I refer to the supply of hot water for domestic purposes, by the use of immersion heaters operated at night when so much generating and other plant is to a large extent idle. This question of thermal storage is, I think, well worthy of industrial research. There are probably in Bristol alone, for instance, 80 000 30-gallon hot-water tanks put out of use by the very extensive substitution of gas and electric cookers for the kitchen range. I suggest that if these were recovered and converted into lagged tanks, or otherwise insulated to prevent loss of heat and fitted with heating elements and such a valve as is fitted in gas and electric steam radiators for turning down the gas or cutting off the current when a temperature approaching boiling point is reached, an extremely valuable storage of energy would be provided. The electrical energy stored by 2½ million gallons of water raised 150 degrees F. in temperature is, I suggest, not to be despised. To compete with gas for heating water, electrical energy would probably have to be supplied at ¼d. per unit. It might be worth ½d. per unit in view of the immunity which electricity provides from fire risks, but the fact that it can be controlled from a distance is an immense advantage, as is also the fact that it can be turned completely off, whereas gas controlled by means of a thermostat is only turned down.

My suggestion is that a simple vibrating relay should be devised to cut the heaters into circuit, one for each tank, at the will of the switchboard attendants, district by district. This could probably be done by superimposing on the supply network a signalling current, which would possibly be sent to certain areas in turn, so as to spread the supply for this purpose over the slack hours. In fact, if this plan is feasible, energy for this purpose could be supplied at any time

of the day or night when there was a sufficient surplus. The thermostat would cut out individual tanks when they were sufficiently heated. For bringing this stored hot water up to boiling point, necessitating the addition of cold water and so conserving the supply, I would suggest the use of small superheaters on each hot-water tap in a house.

As regards the insulation of the tanks, it might be practicable, now that aluminium is getting cheaper and more plentiful, to provide an inner lining on the Thermos principle to existing tanks, exhausting sufficiently the space between the inner and outer walls.

A recommendation for this system, if it can be successfully introduced, would be the fact that if hot water is not used due to a day's absence from home, only the small leakage of heat would be made up and charged for, whilst for prolonged absence the supply should, of course, be cut off at the main switch.

Another utility suggestion which might be worthy of industrial research and exploitation is the following. We have heard of the superimposing of telephonic speech (with the necessary calling facilities by ringing bells, etc.) on transmission lines operated at 30 000 or even 110 000 volts. Of course on underground power cables of any length, or on networks, such speech could not be superimposed. The electrostatic capacity of such cables is too high; but signals of a moderate periodicity probably could be, and there are buzzers on the market which operate at the supply frequency and are intended to take the place of house bells and their batteries.

The supply frequency would, however, probably be too low for my purpose. My requirement is a note which will awake people from a dead sleep, say C in the middle of the treble clef which is, I believe, equivalent to 512 periods per second. Now, if a buzzer could be designed which would operate at this frequency only, I would suggest its use for waking people up, in preference to alarm clocks. If such a signal could be made to operate at several frequencies, a little above and a little below this, so much the better. These frequencies could then be sent over the network at, say, ½-hour intervals from 6 a.m. to 8 a.m. and the renter would be supplied with a small instrument on which he would plug in, or turn a pointer on a dial to the time at which he wished to be called. If in a city the size of Bristol 50 000 renters of this service could be obtained at, say, 10s. a year, an acceptable additional revenue would accrue to the supply company for a small expenditure of energy. I venture to offer these suggestions to the supply authorities for what they are worth.

I will conclude with something in the nature of a vision. When I was in the North of England I erected for telephone purposes trunk lines of H poles braced with iron rods and from 40 ft. to 60 ft. in height. One line ran from Shap, through Penrith, Carlisle and Gretna into Scotland, and on the East Coast a second line ran from Northallerton through Bishop Auckland and Newcastle over the Cheviots to Jedburgh; South and north in other districts they proceeded into Lancashire and Yorkshire respectively, and both into Scotland. Now Professor Robertson, in his Chairman's address * to this Centre in 1916, spoke of various ways of getting cheap power, and he suggested that the Clyde might be dammed. If the great tidal energy of this river could be conserved, converted, and sent down over these lines—which I suppose the Post Office will not require when they can provide trunk telephones underground—it should be possible to supply energy without undue expense to Manchester and Lancashire in general, as well as to the East Coast and Yorkshire. There are also the poles and the lines to every town and village in the country, and my dream is that nearly all overhead plant of this kind will in the future be used for power transmission. Much thicker conductors would have to be employed in some cases, but only a few of them, and the total weight and strain on the poles would probably be much less than at present. The Shap–Carlisle line probably carried 4 tons of copper to the mile. On the minor cross-country lines, energy for lighting and power could be conveyed to every town and village. Over these minor lines it would no doubt be possible to provide the telephone service by means of the high-frequency carrier currents to which I have already referred, or by means of telephone cables suspended on the poles when these are used for power transmission. This double utility should cheapen both services and might lead to the re-population of our rural districts, reviving their industries and greatly increasing the amenities of country life.

Main lines all over the country, having probably a route mileage approximating to 12 000 miles, will ultimately become available for other than their original purpose. May my dream come true, for the turn of the tide of population, at least in part, back from our great centres to the smaller towns and villages would undoubtedly help towards "the greatest happiness to the greatest number." The increased modern facilities for travel will also help to secure this, but not to nearly so great an extent as the widespread provision of cheap electrical energy for light and power and the revival of rural industries.

* *Journal I.E.E.*, 1917, vol. 55, p. 37.

DUNDEE SUB-CENTRE: CHAIRMAN'S ADDRESS

By R. D. ARCHIBALD, Member.

(*Address delivered at* DUNDEE, *10th October*, 1922.)

In surveying the progress which has been made in the design of electrical machinery during the last 20 years, it is interesting to note some remarks made by Mr. Swinburne in his Inaugural Address as President in December 1902 on the subject of "Some Limits in Heavy Electrical Engineering." * Touching on problems generally, he says :—

"It may be well, therefore, to try and look over some of the branches of our great and diverse industry, and see what obstacles are now opposing us, and what are likely to oppose us shortly, and whether the obstacles are insuperable or not. This sort of prophecy is much more difficult than the other, for there can be no credit twenty years hence in having said something that could not be done, even if it has not, while if it has been accomplished the position is still more difficult. Negative prophecy is thus unattractive. But the discussion of our limits not only may have a beneficial effect in making us more modest, but may be a much greater benefit if by focusing our attention on a limit of any development we find either that the obstacle is theoretically insurmountable, in which case we must go round it, or that it has to be scaled in a particular way."

Speaking of efficiency and output of dynamos, he says :—

"We are not likely to make much advance in dynamos now, as we are limited on one hand by the hysteresis loss in iron, which prevents our using higher inductions in armatures, and low permeability which limits our field and armature tooth inductions. It does not seem likely we will now find iron much better in either respect. Nor are we likely to find a better available conductor than pure copper. As insulator we have mica. It looks, therefore, as if we were within sight of our limits in dynamo and motor designs."

Mr. Swinburne went on to describe a type of dynamo in which the field was made to rotate faster than the poles, whereby the E.M.F., and therefore the output of a generator of given size and speed, could be increased. He suggested the application to traction motors of the inverse of this principle, whereby the same output could be obtained from a given size of motor at a lower speed. The principle is virtually contained in the Hunt and Creedy cascade induction motors now in common use, but as far as generators are concerned it never seems to have received much attention. Possibly it may be more developed in the future, but the need for such a complication has largely disappeared since the introduction of the turbo-alternator.

In the light of Mr. Swinburne's remarks, let us now rapidly review the developments which have taken place in the last 20 years and again glance at the limits or obstacles to further development with which we are faced.

* *Journal I.E.E.*, 1903, vol 32, p. 9.

In the development of anything new, whatever it may be, we always find that its design is founded on, and resembles some implement, machine, or even animal which performed the same function before. The dynamo was evolved from the physics department and retained the stamp of the physics laboratory for some time before the engineer took the matter in hand and turned out the dynamo as we know it to-day.

Twenty years ago this change had already practically taken place, for, although Gramme-ring and smooth-core armatures were still being made, they were chiefly for spares or for such purposes as organ-blowing where the hum caused by the toothed armature was objectionable. The bipolar type of field magnet was still lingering in sizes in which it ought to have disappeared, in spite of the arguments advanced in favour of four-pole designs. The reasons adduced for the extra long life of the bipolar machine in this country was that we employed higher speeds than they did on the Continent. But it was soon realized how wasteful in material the bipolar type was, compared with the four-pole machine, and nowadays we find the bipolar magnet only in small machines or in larger machines only where abnormal circumstances combine to make it more expedient, as in certain turbo-alternators and railway motors.

The interpole machine had not yet made its appearance 20 years ago, although the idea was by no means a new one. At that time the load at which a machine sparked was, as often as the temperature-rise, the limit to its output, and the introduction of interpoles had the effect of raising the sparking limit and making us pay much more attention to the question of keeping the machine cool.

Alternators of the Ferranti and Mordey types were still in use, though rapidly becoming obsolete, and the medium-speed alternator which was taking their place was little different from the present-day type. The large low-speed type was becoming even larger, but in a few years its days were numbered as far as steam engines were concerned and the turbo-alternator very quickly took its place. The behaviour of the rotary converter on 50-cycle circuits created doubts in the minds of some as to the wisdom of employing such high frequencies, but it can now be trusted to run automatically in many places. Developments have chiefly been in connection with the regulation of the voltage and automatic starting. Induction motors were largely of the open-slot type, following American practice. The open slots permitted coils to be wound on formers, and barrel windings to be placed in the slots in the same way as in d.c. armatures. The closed or semi-closed slot

necessitated hand winding, which increased the cost of labour considerably, but since more iron was exposed to the air-gap the machine could be made smaller and material was saved. In America, labour was dear and material cheap so that the open-slot type flourished. The winding difficulties in the smaller sizes were soon got over, however, by the use of a slot-opening just sufficient to let the conductors of a coil in singly, and in the larger sizes, in which bar windings are used, by quick methods of soldering the connections of the bars which were pushed through the slots and then joined together. A great many inventions were brought out to get over the difficulty of starting the squirrel-cage type, but hardly any of these have survived, and with the simple induction motor we are not much further on in that respect.

No radical change has taken place in the design of transformers. Some special types have dropped out and, excluding the progress in methods of cooling and insulating for high pressures, there is little to record. The gradual increase in the iron losses due to ageing was a trouble which has since been got over by the manufacturers.

Hopes of long-distance traction by single-phase commutator motors existed in those days just as to-day, but developments have not been in proportion to the hopes; though the single-phase motor has been much improved as far as sparking limits and outputs are concerned.

It would appear, therefore, that there has been no radical departure in the general design of electrical machinery during the last 20 years, and on comparing the appearance of an old machine with a present-day one the chief thing noticeable is the tendency to enclose the working parts in a dust-proof—or is it a fool-proof—case. This is a sure sign that no minor troubles, and also no radical changes in design, are expected.

Before reviewing the limitations which confront us at the present time, let us refresh our memories by examining in what way the output of an electrical machine is limited. We shall take as an example a medium-speed alternator of low voltage. The output is proportional to the terminal E.M.F. multiplied by the current delivered. The E.M.F. is of course fixed by the voltage of the supply to which the alternator is to be connected, but we shall leave out all limitations external to the machine and consider only those set by the material of the machine itself. We can increase the output by increasing either the E.M.F. or the current, and shall first consider the effect of increasing the E.M.F.

We can increase the E.M.F. by raising the speed of the machine. This increases the frequency of the alternations in the teeth and armature core, and therefore raises the temperature of the armature. It also increases the centrifugal stresses in the rotor. After a certain speed has been reached, either the temperature of the armature or the stresses in the rotor will set a limit to any further increase of speed. We could get over the difficulty by designing the machine with fewer poles so as to reduce the frequency of the alternations, and with a smaller diameter so as to reduce the centrifugal stresses, but on further increasing the speed we should eventually be faced with the same problem, and finally arrive at the two-pole turbo-alternator in which we cannot make the poles any less or the speed any higher. Our only way out of the difficulty now is to use a stronger material for the rotor, and iron in which the hysteresis and eddy-current losses in the teeth and armature core are less. But we can also increase the E.M.F. by strengthening the field. By doing so we increase the flux density in the armature. After a certain stage the magnetic circuit becomes saturated and an abnormal amount of energy has to be expended to get any further increase in the field and E.M.F. We can increase the axial length of the machine to get over these difficulties, but we cannot for mechanical reasons do this indefinitely, and we are soon up against the same trouble as before. Our only hope now is to find an iron with lower hysteresis and eddy-current losses and with a higher point of saturation.

This exhausts our methods of increasing the E.M.F., so let us now see how we can get more out of the machine by increasing the current. This will increase the copper losses in the winding and introduce further armature reaction. The former will raise the temperature of the armature and the latter will eventually bring down the E.M.F., so that the output is no further increased. We can neutralize the armature reaction by windings on the poles, and we can increase the section of the copper by widening the slot. But this would entail an armature of larger diameter, which is already limited by the speed. We can deepen the slots, but by deepening them we increase the eddy currents, the reactance voltage, and the tooth losses, so that the other limits will soon drive us back to the limit of conductivity of copper.

If we add a commutator we introduce, due to sparking, new limits to the current, and, owing to the flashing-over which occurs when a certain voltage between segments has been reached, to the E.M.F. The sparking limit can be raised by the use of interpoles, and the flashing-over point by the use of more segments, but there is a limit to the practical width of a segment, so that the use of a commutator sets an absolute limit on the voltage which a d.c. machine can give. I have said nothing about the voltage being limited by the strength of the insulation, for the other limits occur in a low-voltage machine long before the insulation question becomes of serious importance.

The position of affairs to-day is that we are face to face with the limitations due to iron losses and saturation, and the resistivity of copper. Some progress has been made in reducing hysteresis and eddy-current losses by alloying iron with silicon; but we have discovered no better magnetic substance than iron, nor better conductor than copper. We may expect, therefore, that these limits will receive much more attention during the next 20 years than they have during the past. The Sayers dynamo recently described in the electrical Press is merely a further attempt to get round these obstacles by cutting out the armature-core losses and short-circuiting the idle parts of the armature coils, or practically doing away with end connections.

This is not the first attempt in this direction. Disc-type machines have been made on this principle for direct and alternating currents, but there are many

objections to the disc construction, one of the most important being its weakness laterally, so that short-circuits are very apt to destroy the winding. It will be interesting to see to what extent centrifugal stresses will limit the speed and output of this machine.

If the dynamo of the future is going to avoid core losses, we shall have to face the problem of saturation and conductivity. We must bear in mind that these two factors contribute largely to the foundation of the heavy electrical industry. Were it not for the fact that iron is so much more permeable than other magnetic substances, and copper such a good conductor, electrical engineering would probably be by this time past its zenith. Certainly it looks as if further expansion of tramway systems is going to be very much curtailed. The trouble is that the weight efficiency of the internal combustion engine has improved a great deal and that of the electric motor very little.

Is the case quite as hopeless as Mr. Swinburne thought 20 years ago? The applied physics department is a new creation since those days and is busy on those problems at the present time. The exact conditions which render a body magnetic are not yet fully understood. We find that the alloys of some non-magnetic substances form magnetic ones and that alloys of some magnetic ones form non-magnetic ones; also that slight impurities affect the magnetic condition very greatly. It is too soon to say that anything is going to come of this, but further research along these lines will tell us before very long whether saturation is an obstacle which we must get round or can surmount.

When it comes to conductivity the alloys give us no help; for by alloying two metals we always increase the resistance. Experiments with metals at extremely low temperatures show that it is possible to make a conductor have practically zero resistance. It is hardly likely that this will find any practical application at present, though it does not seem beyond the bounds of possibility that it may some day be made use of in turbo-generators if the heat-insulation problem is not too difficult and the energy were transmitted to the external circuit by mutual induction to prevent heat being drawn from the mains.

The important point about these experiments is that they will probably lead us to the solution of the problem of what really is the cause of resistance. Then we shall know whether it is necessary to go to these low temperatures to get better conductivity. If so, and we can find nothing better than our present iron, the prophecy of Mr. Swinburne will probably be good for another 20 years, if not more.

I shall conclude by suggesting a problem towards which it might be advantageous for station engineers or manufacturers of generating plant to turn their attention.

Every effort is being made at present to obtain more effective means of cooling in turbo-alternators and this is a most praiseworthy object to have in view. But little heed is paid to the considerable difference which is made by introducing the cooling medium at a low temperature. For example, let the temperature of the cooling air of a fully-loaded turbo-alternator be t_1 at the inlet and t_2 at the outlet, and let the temperature of the windings of the alternator be t_3. Then t_3 is greater than t_2, and t_2 than t_1. The rise of temperature of the alternator windings is t_3-t_1, and this is practically the same on a cold winter day when t_1 is low, as on a hot summer day when t_1 is high. The consequence is that the alternator may have a considerable overload capacity on a very cold day, and little or no overload capacity on a very hot summer day.

Let the output of the turbine be 100 and the losses in the alternator be 5, so that the output of the alternator is 95 and its efficiency 95 per cent. Let $t_1 = 60°$ F., and $t_3 = 150°$ F. at full load, so that the temperature-rise $t_3-t_1 = 90$ degrees F.

Now suppose that there are 12 degrees of frost so that t_1 becomes 20° F. The rise of temperature being the same as before, t_3 becomes 110° F. and we are left with a margin of 40 degrees F. to work on. On the assumption that the temperature of the winding rises in proportion to the losses, we could increase the armature current in the ratio of $\sqrt{(130/90)}$ or 20 per cent, and bring t_3 back to 150° F. The capacity of the turbo-alternator is therefore 20 per cent greater than when the air temperature is 60° F.

Suppose now we artificially produce the cold by refrigerating the cooling air from 60° F. down to 20° F., and for simplicity let us suppose that t_2 is 60° F., so that the cooling air enters the alternator at 20° F. and comes out at 60° F., In passing through the alternator the air receives an amount of heat practically equal to the losses = 5. This, then, is the amount of heat we have to extract from the air to bring it down to 20° F. again. (If t_2 is less than the atmospheric temperature we should gain a little by using the same air over again.) To get cold air at 20° F. we might have to refrigerate down to −10° F. Now the coefficient of performance of a refrigerator working between the limits of 60° F. and −10° F. is theoretically 6·4. Refrigerators can get within 70 per cent. of the theoretical figures, but allowing for motor losses, etc., suppose that we take the figure as 4. This means that for every 5 units of heat extracted from the air only $\frac{5}{4}$ or $1\frac{1}{4}$ units of work need be done. This work must be added to the losses, which will now be $6\frac{1}{4}$ at full load. We can, however, increase the load by 20 per cent or from 95 to 114, and if we assume the copper loss at full load to be 1·5 the extra copper loss at 20 per cent overload will be $\left\{(1\cdot2)^2 \times 1\cdot5 - 1\cdot5\right\} = 0\cdot65$. The total losses are now $6\cdot25 + 0\cdot65$, that is, say, 7, and the efficiency is

$$\frac{114}{114+7} = 94\cdot2 \text{ per cent.}$$

Hence with a small loss in efficiency the capacity of the station is increased by 20 per cent if the steam turbines and the boilers are able to supply the power. The cost of the refrigerator and the loss of efficiency would have to be set off against the cost of extra generating plant, but circumstances might arise where it would be useful to consider this point, and a liaison between the station engineer and the refrigerating engineer might elicit a number of things which neither had thought of before.

I suggest that this is a matter which might be explored to see whether any advantage could be gained.

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By F. G. C. BALDWIN, Member.

THE PROGRESS AND POTENTIALITIES OF THE TELEPHONE IN THE UNITED KINGDOM.

(ABSTRACT *of Address delivered at* NEWCASTLE, *23rd October*, 1922.)

HISTORICAL.

In the short time at my disposal it is quite impossible to give an adequate conception of the most interesting story which lies behind the development of telephony in this country. It is full of romance and it is perhaps astonishing that, so far, it has escaped more than very casual attention in literature.

On Wednesday, 2nd August, 1922, there passed from this life an inventor who, unlike many other such workers, lived long enough to witness the world-wide application of the fruits of his labour in the interests of humanity. I refer to Alexander Graham Bell, the inventor of the telephone.

Graham Bell really invented the telephone at Boston, Mass., on 2nd June, 1875, being assisted by Thomas A. Watson, an assistant in the electrical workshop of Charles Williams, whither many would-be inventors resorted for assistance in giving practical form to their ideas, and in the years which since have elapsed to the day of his death, at the ripe age of 75, he followed the development of his invention into an enormous industry and one which now furnishes a means of communication employed in every civilized country in the world.

The telephone is now so commonplace that one loses all wonder at its performance and is apt to forget what a really wonderful device it is; in fact, nowadays if it fails to give such constant service as is rendered, for example, by the domestic water tap, it is frequently condemned in no gentle terms. Yet it is extremely doubtful whether the announcement of any invention either before or since has been received with such incredulity or has excited such intense interest as that of the telephone. Mr. J. E. Kingsbury, in an address delivered at one of the meetings commemorating the fiftieth anniversary of the Institution,* refers to his vivid recollection of the feeling of awe which came over him on the occasion of his first experience of telephonic speech in 1878. Incidentally, telephone engineers might not be displeased if the telephone engendered some of that same feeling of awe amongst telephone users to-day and engendered a little more reverence for the instrument than is sometimes accorded it.

Telegraphy was the first real practical application of electrical science to the needs of mankind, and it was to forward the interests of electrical and telegraphic science that our Institution was inaugurated in 1871 as the Society of Telegraph Engineers. In 1878 the telephone was introduced into this country in commercial form; other branches of the electrical profession began to develop at about the same time and, along with telephony, grew into lusty branches before many years had passed. Although, in view of the ruling of the Court in the case of the Attorney-General *versus* the Edison Telephone Company, on 20th December, 1880, that the telephone was a telegraph within the meaning of the Telegraph Acts of 1863 and 1869, the designation "Society of Telegraph Engineers" might have sufficed to embrace the telephone also, yet the development of the sister branches of electrical science was so vigorous that the old title became inadequate to indicate the objective and scope of the Society, and, consequently, in 1881 it was altered to "The Society of Telegraph Engineers and Electricians," only to be changed again when the present title "The Institution of Electrical Engineers" was adopted in 1883.

For some time the telegraph and the telephone remained in the background, and it was not often that the deliberations of the Institution were directed towards the subject of telephony. So scanty indeed at one time were the literary contributions on telephony to the Institution and also to the technical Press, that it might not unreasonably have been concluded that the subject did not present a sufficiently wide field for exploration by the potential author. It was not, however, for this reason that telephone subjects were not more frequently treated.

While the principal telephone patents were in force the United Telephone Company was compelled very jealously to guard its rights and, while actively engaged in its numerous legal disputes, adopted a highly conservative attitude. Publication of its policy and methods of working were absolutely banned; at one time its officers were not permitted to read papers before the Institution and they were forbidden even to attend its meetings. Consequently, commensurate with the importance of telephony, there was a dearth of literature on the subject during the period in question, and it was a long time before the atmosphere created by the stringent secrecy and exclusiveness of the United Telephone Co. was dissipated.

The Post Office also has always been essentially conservative so far as publicity is concerned, and has never encouraged advertisement either of its policy or of its engineering and scientific achievements, although it has always been ready to furnish information and tender advice to interested parties. In comparatively late years only has telephony begun to take its rightful place in the proceedings of Institutions which exist for the advancement of engineering science.

The condition of the telephone system and the efficiency of the telephone service in this country have together been a source of keen discussion, and the subject of no little criticism ever since the telephone became established as a practical proposition. In

* *Journal I.E.E.*, 1922, vol. 60, p. 428.

1878, people were amazed and almost incredulous at the idea of carrying on, by electrical means, conversation between points far distant one from another, and yet, in spite of the fact that telephone development in the United Kingdom has never been considered to be comparable with that which has occurred elsewhere, and particularly in America, progress was so rapid that in the space of a few years the old adage "familiarity breeds contempt" was once more exemplified, loudly voiced complaints being made that the telephone service was woefully inefficient, that speech was interfered with by extraneous noises, that sometimes conversation was interrupted, and that delays were experienced in establishing connections. Since that time vast developments and great improvements have taken place and yet similar and no less vehement outbursts of complaint are still not uncommon.

The master telephone patents did not expire until 1890 and 1891, and the United Telephone Co. which owned them during the greater part of the time they were in force farmed them out to other companies to exploit the provinces, and itself undertook the telephoning of London. To this Company fell the lot of guarding the patent rights which it held for the whole of the country, and so numerous were the infringements that it was found necessary to devote no little energy to this end, a fact which to some extent perhaps detracted from the main purpose for which the Company existed, namely, the provision of telephone intercommunication.

During, and for a little time after, the period in which the several subsidiary companies which had been formed were consolidated as the National Telephone Co., there was much organized agitation advocating treatment of the telephone question in different ways. The Government was greatly perplexed by the situation and the Company was kept in a state of suspense and doubt as to the outcome.

All this was not good for the telephone service, and the competition recommended by the Select Committee of 1898 eventually established by venture into the telephone field of certain municipalities, after prolonged agitation by them to be licensed to institute local telephone service, did not mend matters. On 5th April, 1896, the Post Office acquired the telephone trunk-line system of the National Telephone Co. in order that the revenue which it was alleged the long-distance telephone service withdrew from the telegraphs might revert to the Government and in order that facilities for inter-town communication might be available to prospective competitors of the National Telephone Co. The Post Office also entered seriously into the telephone business at about this time and in 1902 inaugurated its London telephone system. Recognizing the futility and serious disadvantages in the public interest of competition between rival telephone administrations, and in spite of the recommendations of the Select Committee of 1898, they wisely arranged in opening their telephone service to co-operate rather than compete, in the strict business sense of the term, with the National Telephone Co. for the remainder of that Company's license, and the metropolitan area was therefore saved from the throes of competition and the somewhat undignified proceedings which occurred in some provincial towns.

During the ten years 1902–1912, a most important and eventful period in the history of the telephone in this country both commercially and technically, Mr. Frank Gill, our President, occupied the position of Engineer-in-Chief to the National Telephone Co.

The election in this country of Mr. Gill as President of this Institution has been paralleled in America, where a similar honour has this year been paid to telephony by the election to the Presidential chair of the American Institute of Electrical Engineers of Dr. Frank B. Jewett, formerly Chief Engineer and now Vice-President of the Western Electric Co., the manufacturing and engineering section of that vast administration the American Telephone and Telegraph Co.

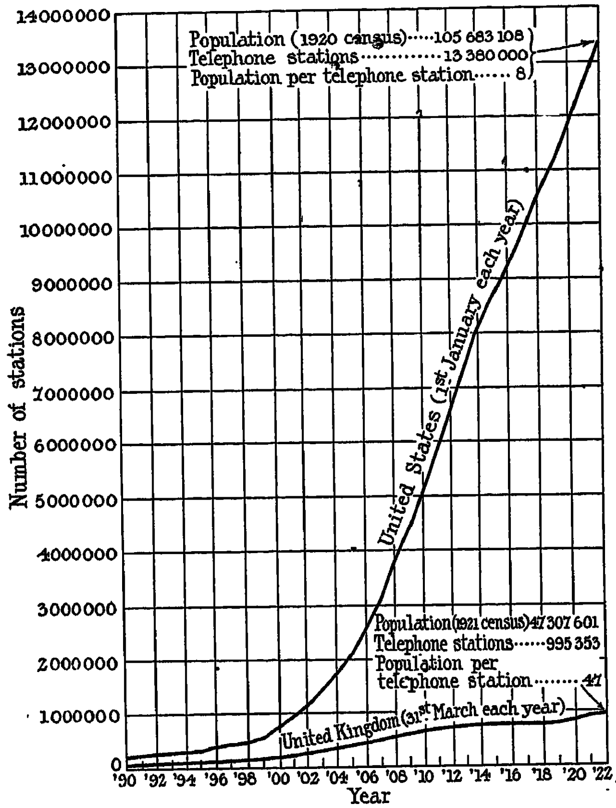


FIG. 1.—Comparison of telephone development in the United Kingdom and the U.S.A.

The Telephone Agreement dated 2nd February, 1905, entered into between the Postmaster-General and the National Telephone Co., which provided for purchase by the State of the Company's system, was the first tangible indication of the ultimate unification of the telephone system of the United Kingdom, but the agreement did not take practical effect until 1st January, 1912.

The total staff of the National Telephone Co. transferred to the Post Office at this time numbered approximately 18 000. Of this number about 7 000 were engaged almost exclusively upon engineering work and, when added to the existing forces of the

Post Office Engineering Department which numbered roughly 9 000, brought the total up to 16 000.

Within two years the staff had increased considerably and a good deal of work had been accomplished towards the unification of the system. Comprehensive schemes for the replacement of obsolete plant and the installation of new plant on a generous basis to meet anticipated development were in full swing when, unfortunately, the Great War intervened and put a stop for more than five years to all but imperatively necessary work.

During this period some 13 000, corresponding to more than 50 per cent. of the engineering staff of the Post Office, upon whom devolved the maintenance

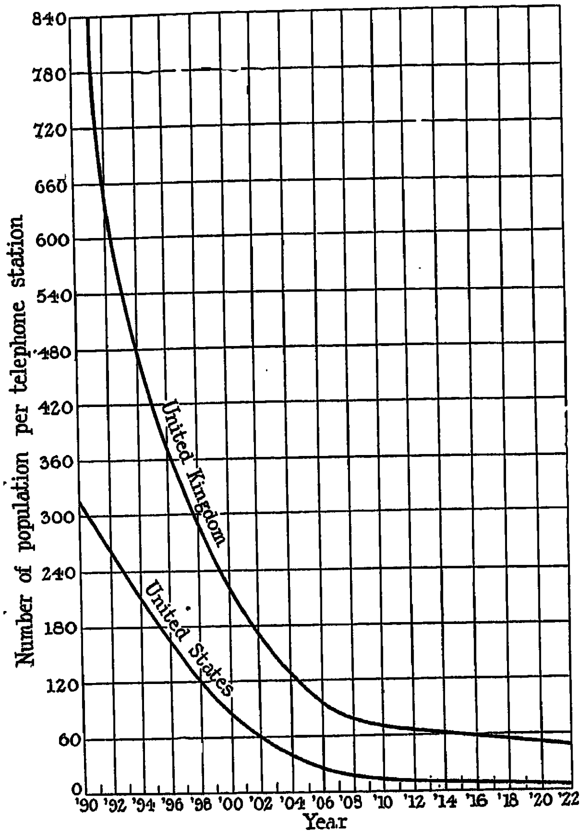


FIG. 2.—Comparison of the number of population per telephone station in the United Kingdom and the U.S.A.

of the telephone service, were liberated for war purposes exclusively, and the remainder, in addition to carrying on the home telephone service under most trying conditions, also undertook services for the armed forces and associated with the Home Defences, services which have never been and never can be adequately realized by the uninitiated.

Since the armistice was declared, the telephone service has been carried on under difficulties no less than those which had to be contended with during the war. High, uncertain, and fluctuating prices, depletion of highly skilled staff, and shortage of the widely varying classes of materials and plant employed in telephony, have seriously delayed progress with the schemes which were in contemplation at the outbreak of war. Consequently, in many cases service has had to be and is still being carried on with plant that is obsolete and even past its physical life.

COMMERCIAL DEVELOPMENT.

Development of the telephone in the United States since about 1900 has been phenomenal, until at the present moment there is one telephone station to approximately every 8 of the population, which totals approximately 105 millions. The development in the United Kingdom, with a population of 47 millions, has never attained to more than one telephone station per 49 of the population. The telephone development in the United States and in this country is compared graphically in Figs. 1 and 2.

It may be that the comparatively slow growth of the telephone in the United Kingdom is but a natural lag due to inherent British conservatism, and that in the near future the growth of the system on this side of the Atlantic may compare favourably with that which has taken place in America. Telephone development in this country will, however, depend primarily upon a return of commercial prosperity, and also upon a better appreciation on the part of the British public of the facilities afforded by a liberal provision of telephones in business houses and private residences.

I should like to take this opportunity of directing attention to the benefits to be derived by any community from extended use of the telephone. It will be obvious that the facilities afforded by telephone

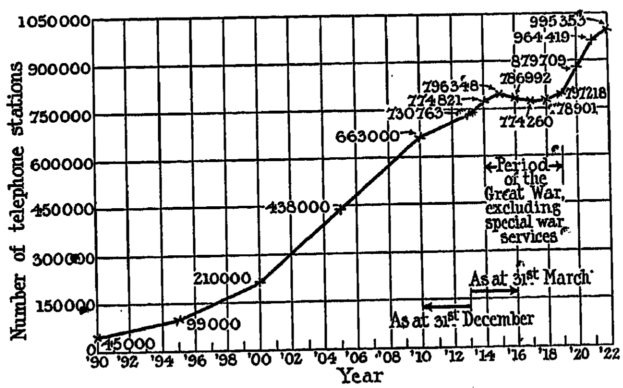


FIG. 3.—Telephone development in the United Kingdom.

intercommunication service are increased with every subscriber added. I need not enlarge upon the advantages of telephone communication, but I venture to express the opinion that a large increase in the number of telephone subscribers would be highly beneficial to the commercial and industrial as well as the social life of the Kingdom. I have reason to believe that one of the causes why the telephone service does not develop satisfactorily is that many people refrain from becoming subscribers because the majority of those with whom they would desire communication are themselves non-subscribers.

So long as this conservative and somewhat illogical attitude continues it seems obvious that the telephone system cannot develop as it should, and the extended

facilities which would follow from a more universal use of the telephone cannot therefore be secured.

The growth in telephone stations in the United Kingdom is illustrated in graphical form in Fig. 3. I have included this curve, which is similar to that shown in Fig. 1 except that it is drawn to a larger scale, in order to illustrate more particularly the effect of the war on telephone development in the United Kingdom. The unprecedented depression in the curve during the war period will be observed, as also the surprising fact that the loss sustained during the 4 years of war has almost but not quite been regained after a further 4 years, in spite of the difficulties which have been experienced.

Telephone Switching.

The mere transmission telephonically of a communication between two fixed points is a matter which presents no great difficulty, and nowadays can be accomplished with little risk of interruption, but the introduction of the essential facilities for signalling and switching increases considerably the possibility of the occurrence of faults.

In the United Kingdom there are at the present moment upwards of a million telephone stations any one of which, with some comparatively few exceptions, may require connection with any other. When one considers for a moment the various operations and the numerous pieces of electro-mechanism possibly involved in the establishment of such a connection, and the combinations which are possible, the immensity of the system and its complexities may be more readily appreciated.

As is well known, attempts have been made in various ways to dissociate, as far as possible, signalling devices from the speaking circuit and, so far as is commensurate with efficient and economical practice, this has been effected.

The earliest switching appliances, from which the present-day manual switchboards have been evolved, were of a crude character. As early as 1879 there were two distinct types in use in this country; the one employed by the company formed to exploit the Bell patents depended upon flexible cords for establishing connection between one subscriber and another; the other, adopted by the Edison Telephone Co. which worked the Edison patents in competition with the previously mentioned and original Company, being an adaptation of the Umschalter switch much used at one time for telegraph switching. Thus the vexed question of the cordless *versus* the cord switchboard arose at an early date in the history of telephony, but the latter eventually proved its superiority, in spite of the trouble arising from the early type of flexible cord, and the cordless type of board was abandoned.

The rapid development of the telephone soon created, at the larger exchanges, serious difficulties in switching, which were eventually surmounted by the invention of the multiple.

It is not generally known that, although the multiple was invented and eventually perfected in America, it was devised independently in this country, much about the same time, by Mr. F. B. O. Hawes of the United Telephone Co., and two switchboards constructed under his direction were eventually brought into operation in London.

Unfortunately, Mr. Hawes did not benefit by his invention, being forestalled by the patenting of the American product in this country; consequently, multiple boards being essential here, they were for the most part supplied by the Western Electric Co. who acquired the patent rights. The first Western Electric multiple switchboard to be installed in this country was brought into service at Liverpool in 1884.

Early signalling was by means of batteries and ordinary trembler bells, which soon gave place, however, to magneto ringing, and the magneto system, apart from the call-wire system which was soon abandoned, held sway generally for a lengthy period, and, owing largely to the effect of the war, is still in considerable use although now regarded as obsolescent.

From the very inception of telephone switching in 1878, engineers have consistently striven to reduce manual labour in operating by the introduction of automatic appliances, with the object of minimizing the mental and physical effort of the operator, and of increasing the speed of operation and the number of calls which can be handled in a given period.

One might trace at some length the measures which have been introduced from time to time in the adoption of automatic devices as aids to manual operating, but it will perhaps suffice to mention only the step in this direction which was taken in the substitution of the common battery or relay system, as it was first termed, for the magneto system which it largely displaced. It is true that the prime purpose for which the common battery system was devised was to enable the primary batteries, previously necessary at the subscriber's station, to be dispensed with and current to be supplied to the transmitters from a centrally situated battery, but it is also true that by means of the relays and lamp signals, which form one of the salient features of the common battery system, the operating facilities were greatly improved, principally inasmuch as the operator was saved the labour of replacing by hand the shutters of electro-mechanical indicators.

The common battery system remains to-day very much what it was when first introduced in 1900, no drastic alterations either of the circuits or the mode of operation having been made. It realized expectations and a high standard of service was quickly reached, but it soon became apparent that there was little likelihood of any further material advance being made in telephone switching by this method, and consequently attention was turned to the possibilities of switching by machinery and the elimination, partially or entirely, of the manual element.

The introduction of full automatic switching whereby human intervention at the exchange is rendered unnecessary was not actually a natural development of the application of automatic appliances to the manual system. There were reasons why this could not be so. So-called automatic telephony was an invention which involved the employment of apparatus entirely distinct and different in principle and design from that employed in manual working, and was developed quite inde-

pendently of the manual system which continued to be improved concurrently.

The removal of certain disabilities from which the automatic system suffered at first were essential before its adoption as a switching medium in this country was desirable, and it was not introduced here until its ability to fulfil the necessary functions satisfactorily had been demonstrated.

The period in which the automatic system was being developed in America was not a propitious one for its trial here. Because of its early expiring license the National Telephone Co. was disinclined to incur capital expenditure from which the financial return was doubtful, and it was therefore left to the British Post Office to conduct the first experiments in automatic

(3) Whether the British public would receive favourably the automatic system.

(4) The relative costs of machine and manual switching.

(5) The relative merits of the different systems on the market.

The first exchange to be opened was of the Strowger type, but since this system assumed practical form, a number of other systems have been developed, and the experiments conducted by the Post Office have included trials in actual service of five different systems in all, to which it is expected another will shortly be added.

A complete list of the automatic exchanges already opened and immediately in contemplation by the British Post Office is appended.

AUTOMATIC TELEPHONE EXCHANGES ESTABLISHED BY THE BRITISH POST OFFICE: 1912–1922.

	Exchange	Type of equipment	Date opened	Capacity	
				Of present equipment (1922)	Ultimate
1	Epsom	Automatic Telephone Manufacturing Co.	18 May, 1912	600	1 500
2	Official	ditto	13 July, 1912	900	1 500
3	Hereford	Lorimer	1 Aug., 1914	500	900
4	Darlington	Western Electric Co. rotary	10 Oct., 1914	800	2 260
5	Accrington	Automatic Telephone Manufacturing Co.	13 Mar., 1915	700	1 500
6	Portsmouth	ditto	29 April, 1915	5 000	7 000
7	Chepstow	ditto	7 July, 1915	75	100
8	Newport	ditto	14 Aug., 1915	1 800	3 500
9	Paisley	ditto	15 July, 1916	1 600	2 150
10	Dudley	Western Electric Co. rotary	9 Sept., 1916	500	1 600
11	Blackburn	Automatic Telephone Manufacturing Co.	14 Oct., 1916	2 200	4 400
12	Leeds	ditto	18 May, 1918	9 600	15 000
13	Grimsby	Siemens	14 Sept., 1918	1 860	4 000
14	Stockport	ditto	23 Aug., 1919	1 300	2 260
15	Ramsey (Hunts) ..	Siemens (Village)	24 Oct., 1921	40	50
16	Hurley	ditto	20 Dec., 1921	25	50
17	Fleetwood	Relay Automatic Telephone Co.	15 July, 1922	480	700

AUTOMATIC TELEPHONE EXCHANGES ON ORDER BY THE BRITISH POST OFFICE: OCTOBER 1922.

	Exchange	Type of equipment	Capacity	
			Initial	Ultimate
1	Dundee	North Electric	3 500	5 000
2	Southampton	Siemens	3 500	5 500
3	Swansea	Siemens	3 200	6 800
4	Marton (Yorks)	Automatic Telephone Manufacturing Co.	80	230

switching in this country. These experiments were commenced in 1912 and were undertaken in order to ascertain:

(1) Whether automatic apparatus would fulfil satisfactorily the necessary switching functions.

(2) To what extent, if any, the British climate would affect prejudicially the operation of machine switches.

The first three of the five questions previously enumerated have now been answered favourably to the automatic system, and it now remains to dispose of questions (4) and (5).

Time will not permit of discussion of the relative advantages of the automatic and manual systems of switching, nor of consideration of the several factors

which are involved in determining the economics of the question. It is impossible to enunciate any rule for guidance in the choice of a system, either as between automatic and manual or as between the different automatic systems, and it is necessary that each case should receive consideration according to its distinctive merits.

Hitherto the policy adopted by the British Post Office has been confined to the application of automatic working to individual exchanges situated in various parts of the country, and in no case has a self-contained area including a number of exchanges been dealt with as a whole. Plans are, however, now in hand for the establishment of automatic working in a number of multi-exchange areas wherein the whole of the local traffic between exchanges situated therein will be dealt with exclusively by machine switching.

The problem of providing switching facilities by automatic means in an area containing several exchanges possesses many points of difference from the old problem in which manual switching only was concerned, and if, as seems highly probable, machine switching is introduced on an extensive scale the local telephone exchange systems of large commercial and industrial centres will differ in many essentials, other than the purely automatic one, from those to which we have become accustomed. Our previous conceptions and notions concerning the lay-out of large telephone systems will in that case need considerable adjustment.

With full automatic working in a local area, communication between subscribers connected to different exchanges may be effected as rapidly as between one set of switches and another situated in the same exchange, and the disadvantages which attach to junction working in a manually operated group of exchanges are therefore removed. Moreover, by reason of the rapidity of operation of automatic switches, a group of junction circuits may be worked at maximum efficiency.

These factors operate in the direction of increasing the number of exchanges and reducing the number of junctions which would apply with a manual system. As in a given area the number of exchanges may be increased, so the areas served by each exchange will be reduced in extent and the average length and, consequently, the cost of subscribers' lines are thereby reduced. Thus there are possibilities of effecting large savings in cost of line plant, a very heavy item in the capital investment of any telephone system, by the establishment of machine switching.

Automatic working possesses certain attractive features which commend it also for the supply of service in remote and sparsely populated districts. In country villages, where the number of subscribers is small and the traffic light, it is not reasonable to expect from the manual system the same standard of service as is applicable in an exchange where the number of subscribers is sufficient to justify unbroken attendance at the switchboard; and night service which, at some small country exchanges, is not at present available, is also a problem.

The employment of the automatic system at such places entirely removes those disabilities which are almost inseparable from a manually operated system, but, unfortunately, other difficulties of a technical and economic character are introduced which up to the present time have not been surmounted, despite the close attention already bestowed upon the question.

When the special problems pertaining to the village automatic exchange have been solved, as perhaps they may be in the near future, developments in the application of automatic working to such cases will, no doubt, proceed rapidly.

Long-distance Communication.

There is something enthralling in accomplishing the interchange of speech over long distances and, ever since the telephone was first invented in 1876, endeavours have constantly been made to extend still further the distance over which telephonic speech might be satisfactorily conducted.

From a practical point of view the possibilities of long-distance communication within this country are definitely restricted by reason of its very limited boundaries, but in America, where the telephone flourishes more than in any other country in the world owing to the vast size of the continent, there are ample opportunities for development in long-distance service, and it is in America naturally where long-distance, as well as short-distance, service has been developed with great enterprise.

The longest distance across which telephone speech has, so far, been transmitted successfully is between Catalina Island in the Pacific Ocean and Cuba, a distance of something in excess of 5 500 miles. This distance included a length of 30 miles between Catalina Island and Los Angeles on the mainland bridged by a radio telephone connection; and between the Island of Cuba and the United States, the longest deep-sea telephone cable in use formed another link in the chain.

Up to the early nineties even the relatively low specific inductive capacity of the composite dielectric of the dry-core or paper-core cable was sufficient to render circuits carried in such cables greatly inferior in transmission value to the cheaper type of circuit comprised of bare overhead wires supported on poles, and consequently the latter form of conductor weighing up to as much as 800 lb. per mile was employed, to the exclusion of underground conductors except where the latter were absolutely unavoidable.

Although the limiting distance of speech over conductors of various types was fairly well known, and though the reason which limited that distance was partially but imperfectly understood, it was not until the theoretical works of Oliver Heaviside, published in this country so far back as 1887, were investigated and put into practical form and application by Dr. M. I. Pupin of New York in 1899 that the phenomena which accompanied the electrical transmission of speech came to be properly understood and a complete knowledge of the subject of telephonic transmission was built up.

The application of Pupin's work in the form of an inductance coil for the nullification of distortion and improvement in transmission, now known as line loading, and its results are already matters of past history and

have become common practice. The application of line loading resulted almost immediately in extension of the use of underground conductors for longer distances, but the effect of loading in this country was, perhaps, more particularly in securing economy in underground line construction by a diminution in the gauge of wire required.

The benefits derived from the application of loading to subterranean conductors were insufficient to permit of the substitution of open by underground wires for long-distance circuits, even in this country. It is in fact only within the past year or two that communication by telephone over conductors exclusively underground from end to end of the country has been rendered possible by the introduction of the telephone repeater, a device which has been the dream of telephone engineers ever since the telephone was invented.

The application of the thermionic valve in the production of the modern telephone repeater is too well known to need further mention.

The long-distance telephone lines of this country are now steadily trending towards a comprehensive system of conductors of comparatively light gauge, laid exclusively underground, loaded at intervals of approximately 2 000 yards, linking up a series of repeater stations situated approximately 50 miles apart. Thus the one-time simple metallic loop between one centre and another is changing its form and becoming, as it were, more and more assimilated with the speaking apparatus. Although there are difficulties in the way, some known and some perhaps unknown, of which therefore it is yet too early to speak, there is little doubt that they will be surmounted in due course and that a long-distance telephone system immune from the interruptions and disturbances due to climatic and other influences, which are inseparable even from the best-constructed overhead systems, will be secured.

Line Plant.

Since the resuscitation of Heaviside's theoretical work brought about by the investigations of Pupin, a fresh light has been thrown upon the functions of the line in the transmission of speech, and in very quick time an entirely new branch of telephonic science came into being under the term "telephonic transmission."

The result was what amounted to a revolution in underground line practice. The 20-lb. conductors universally used for subscribers' circuits soon gave place largely to wires of 10 lb. per mile, to be followed later by 6½ lb., and mechanical considerations chiefly limit the use in certain circumstances of conductors of still lighter gauge.

It became possible to design lines specifically according to the particular functions which they would be called upon to perform, and the altered aspect introduced many complexities in the design of economical cable systems. The problem is still further complicated by the provision which must be made for that unknown quantity, future development.

The considerations which are involved in the distribution of telephone lines are totally dissimilar from those which apply in the distribution of gas, water and electrical energy. With the latter, one main frequently serves a large number of consumers and, within certain limits, overloading may be resorted to without serious results; whereas for each telephone subscriber an independent pair of wires must be provided and maintained in a satisfactory state of insulation between each subscriber's station and the exchange. Consequently, a telephone line system has no flexibility apart from the special provision of spare conductors. Furthermore, water, gas and electricity supply are regarded as necessary, whereas in this country telephone service is not, and arrangements may therefore be made without risk for supply of the former into all premises. Telephone service is not by any means universal, and fluctuations are constantly occurring which it is difficult to cater for at short notice and reasonable cost. Consequently, flexibility is secured by completing distribution, wherever possible, by means of overhead wires radiating from distributing points to which a predetermined number of spare pairs of wires over and above the initial number of working circuits is provided.

In the construction of telephone lines the most notable advance made in telephone history has been undoubtedly the production of the dry-core cable.

Although the telephone dry-core cable originated in the United States, it is interesting to remember that as early as 1843 William Fothergill Cook invented, for telegraph purposes, a system of cable which was in effect "dry core." Metallic conductors insulated with a fibrous material were enclosed in an iron tube charged with air at a maintained pressure of about 3 lb. per square inch for the purpose of excluding moisture. The point of difference between the modern paper-core cable and Cook's system was that whereas in the former dry air is utilized as the staple insulating medium, the paper being introduced merely to maintain the wires in separation, in Cook's system the insulation was in reality dependent upon the permanent covering which enveloped the wires, but that covering was nevertheless rendered effective as an insulator by the presence of dry air.

A problem which has always presented particular difficulties is the effective termination of dry-core cable. Even to-day, after more than 30 years' experience, the means available for termination cannot be regarded as satisfactory and I commend the matter to those most intimately concerned for investigation, in the belief that a satisfactory solution would be amply repaid.

Conclusion.

In this necessarily short dissertation I have attempted to give a résumé of the circumstances in which the telephone has been developed in this country from its establishment as a commercial project up to the present day, and to indicate very broadly its immediate possibilities.

Time has not permitted even casual mention of the many troubles which the telephone has experienced, but it will no doubt be apparent that the varied tribulations and vicissitudes through which it has passed have rendered its life a most eventful one.

It is now confidently anticipated that its troubles, if not ended, are at least moderated sufficiently to admit of a development which will be creditable to the country.

LIVERPOOL SUB-CENTRE: CHAIRMAN'S ADDRESS

By B. Welbourn, Member.

(*Address delivered at* Liverpool, *6th November,* 1922.)

During the year it has been my privilege to pay a second visit to Canada and the United States, and to see for myself the immense progress which has taken place in all things electrical during the past 15 years.

Telephony.

The first thing that impressed me was the extensive use of the telephone both for short and long-distance work. Owing to the high price of labour and the shortage of domestic servants, the telephone is a necessity in the majority of homes. The lady of the house has much of the housework to do and necessarily gives her orders to the tradesmen by telephone. In the hotels there is not entire privacy, as even in the bedroom there is usually a telephone.

There are now approximately 14 300 000 telephone stations in the United States. Of these, about 850 000 are on the Strowger system as made in Liverpool, and about 40 000 are of other types. The annual growth of all stations is 6 per cent, but it is significant that the annual growth of automatic stations is approximately 10 per cent. The telephone companies, of which the Bell System is by far the largest, make it easy for people to telephone or telegraph, and the use of both methods has become almost a habit. As illustrating the extent of the use of the telephone, I was told in Chicago that there is one telephone to every five people, while in Los Angeles, California, with 700 000 people, there are over 170 000 telephones, i.e. one to every four people, and telephones are there being connected up at the rate of 290 per working day with no sign of finality ahead. To many Liverpool engineers a very interesting feature of this will be that the whole system in Los Angeles is being converted to the Strowger automatic system as quickly as the plant can be delivered from Chicago. It was also interesting to learn that two exchanges are being equipped in New York with automatic telephones.

Long-distance telephony has made considerable progress, and it is now possible to telephone from Catalina Island, off the Pacific Coast, to Havana in the island of Cuba. This telephone transmission is of more than ordinary interest, as wireless telephony is used between Catalina Island and the Californian coast and is there joined in series with the land line to the Atlantic coast whence messages pass over the loaded submarine cable to Cuba—a distance of approximately 4 000 miles. I understand that, for this purpose, both the physical and phantom circuits are used over the land trunk lines.

Very severe gales with snow are experienced in the Eastern States, and the consequent disorganization of service in the winter is having the same effect as in England, namely, the placing of main transmission circuits underground with paper-insulated lead-sheathed cables to which Pupin loading coils and thermionic valve repeaters are attached, while experiments have shown that it is now possible to telephone experimentally over 15 000 miles of such loaded underground circuits, although the present commercial limit is about 1 000 miles.

One very noticeable feature in telephone work in America is the free way in which lead-sheathed cables are used overhead. In these cases the lead sheath is alloyed with 1 per cent of antimony to harden it and to improve the crystalline structure, and the cable is then suspended from a messenger wire by short supports at frequent intervals.

Among the interesting things shown to me were the first coil of wire through which the late Dr. Alexander Graham Bell sent his first telephone message, and the loud-speaking telephones used by President Harding when addressing a crowd of 100 000 people at the Unknown Soldier's funeral at Arlington Cemetery. Simultaneously, by means of special arrangements, he addressed audiences of similar size at San Francisco and New York. There appears to be no real technical difficulty in speaking simultaneously to audiences wherever there are telephone exchanges.

Broadcasting.

Owing to the early lack of control in broadcasting stations, of which there are about 500, affairs seem to be in a chaotic state in the United States, and admiration was expressed for the leisurely but orderly way in which the matter is being tackled in this country.

It is estimated that there are about 2 000 000 wireless telephone reception sets in the United States, of which one half have been made by manufacturers and one half by amateurs. The manufacture appears to have outgrown the demand and the makers were said to be loaded up with unsaleable stock. Whether this was due to a seasonal slackness of demand, or to the interest in wireless telephony dying out, remains to be seen. It seems significant, however, that a good deal of second-hand wireless apparatus is being offered for sale.

In New York I had the pleasure of being present when Senator Marconi received the Franklin Medal of Honour and of hearing his address to the joint meeting of the American Institute of Electrical Engineers and the Institute of Radio Engineers. He dealt with the position of wireless telegraphy and telephony generally, and gave a good deal of information regarding his resumed experiments with 15-m wave-length telephony, with which he can now get commercial speech over a distance of 120 miles, together with very close direction. It would seem that the use of such a system, which

is outside the ordinary commercial range of wavelengths, should have considerable possibilities for ship-to-ship and ship-to-shore work and also in public utility work, as considerable secrecy can be obtained. The advantages of ship-to-ship and ship-to-shore work under foggy conditions seem to be too obvious to need argument.

ELECTRICITY SUPPLY.

I hope to say something here which will encourage and stimulate electricity supply engineers to further efforts in promoting the use of electricity in this country.

To show the extent to which electricity is used for lighting in the United States and in Canada, I would mention that in the month succeeding my departure from Liverpool I saw only a single gas flare used for illuminating purposes; that was in connection with some suburban street lighting about 10 miles from Chicago I did not, I think, see it again during the succeeding 25 days, except in the streets of Pittsburgh, Pa., where there is ample natural gas, and until I saw it from the Elevated Railway in New York through an open window of some old property.

The New York Edison Company alone has 600 000 kW of plant installed, and in Chicago the Commonwealth Edison Company has 626 450 kW, of which 230 000 kW is in the Fisk-street station. The maximum demand in this city was well over 500 000 kW in Decemer 1921. With a population of 2 700 000 people there are 536 982 consumers, of whom 425 200 are residence consumers, and the total number of kilowatt-hours developed by the company in 1921 was 1 928 271 940, i.e. 714 kWh per head of population. The number of new consumers added in 1921 was 62 287, and a car-load of meters alone is required per week to keep pace with the new service work. The total capital investment is $136 310 574, say, £30 000 000.

Let us compare these figures with those for Greater London with a population of $8\frac{1}{4}$ million people. Taking first of all the company and municipal undertakings, thus for the most part excluding all railway load, from the period 1919–1920 to 1920–1921 the total increase in the number of consumers was in round figures 25 000, bringing the total up to approximately 340 000. During the same period the increase in the plant installed was about 12 000 kW. There was an increase of nearly 40 000 000 in the kWh sold, bringing the total up to nearly 700 000 000. The total capital investment now stands at about £38 000 000, exclusive of the amount specially invested in power houses for transportation supplies.

To the above figures we can add approximately 560 000 000 kWh for the total units used for transportation, bringing the approximate total units for the last complete year to nearly 1 300 000 000, that is, about 155 per head of population. Comparing this with the 714 kWh per head of population at Chicago, it will be realized at once what an immense amount of leeway has to be made up in the capital city of our country alone before the use of electricity reaches the state of development attained by our American cousins.

At the risk of wearying you, I want to drive the point home by giving you data for the whole of the State of California and a few other places for 1921.

Number of consumers in California ..	843 011
Connected load, in h.p.	2 959.413
Employees	20 300
Pay-roll	$31 227 496
Taxes	$6 049 577
Miles of wire	127 382
Oil consumed—barrels (no coal or wood)	2 840 395
Total investment	$448 669 330
Total kWh generated	4 000 479 010
Total kWh sales	2 662 653 511
Power plant capacity	1 463 009
Total population of States	3 426 536
No. of kWh per head of population ..	777

In California, where the electricity supply is regulated by the Railroad Commission very much in the same way that it is governed in this country by the Electricity Commissioners, there is very little, if any, over-lapping of territory on the part of the electricity supply authorities. They seem to work together harmoniously and to have made many voluntary arrangements for the purpose of interchange of power. Practically 100 per cent of the houses in California are lighted by electricity exclusively, and, generally speaking, it may be said that the development of California depends very largely on electric power.

I should like to illustrate my meaning by giving a few particulars to show the way in which the electrical habit has been cultivated in this State. The Southern California Edison Company has 380 000 h.p. installed, chiefly in hydro-electric stations, and has so much faith in the future that it is proceeding with the development of an additional 1 220 000 h.p. The present output is distributed over their area of 56 873 square miles, with a population of 1 500 000 people by means of a network of over 10 000 miles of transmission and distribution lines. It supplies energy for 312 communities, furnishes power for 2 000 miles of interurban electric railways and for the irrigation of 1 000 000 acres of land. They directly supply 276 000 consumers, while other Southern Californian systems supply 240 000 consumers, thus making a total of 516 000.

Further north in the same State the Pacific Gas and Electric Company transmits and distributes over an area of 58 481 square miles with a population of 1 715 959 and 285 206 consumers, some of whom are distribution companies. To deal with this load, the company has a total installed capacity of 481 836 h.p., of which 421 750 h.p. is hydro-electric, and approximately 60 000 h.p. is steam-generated in oil-fired stations. Their supply is distributed over 9 971 miles of overhead lines.

Turning to our own Empire, we find rapid development in Canada. Apart from the great systems in Quebec centring around Montreal, etc., and those in British Columbia controlled by the British Columbia Electric Railway Company, etc., there is the large Government and municipal partnership scheme called the Hydro-Electric Commission of Ontario, which owns and makes use of generating plant at Niagara to the extent of 427 000 h.p., and other sources of power, is covering the whole province with a network of 110 000-volt

and other lines and serves a population of 1 667 165. The Commission had 268 743 consumers on 31st October, 1921, with a maximum demand in June, 1922, of 360 268 h.p., and I saw for myself a great deal of the use which is made of the power from Niagara in the Commission's area from wayside farms to large undertakings such as that at Toronto. The Commission has succeeded in reducing very materially the cost of electricity to the consumer in Ontario, with the result that its use is extending rapidly. For instance, the Toronto undertaking had 12 000 consumers 10 years ago, whereas it now has 80 000. In Toronto the domestic consumption in kWh per consumer per month was 27 in 1914, whereas in 1921 it was 48, an increase of 78 per cent; the wholesale rates per kWh per annum have been reduced from $18.50 in 1912 to $17.00 in 1921, a decrease of 8 per cent, while the net cost per kWh for the domestic consumer has been reduced from 4·4 cents in 1913 to 2·2 cents in 1921, a decrease of 50 per cent.

The question that I asked myself is: How is it that this great business is done? In the first place one would expect that the electricity supply rates for power and domestic users must be considerably lower than in this country. With the exception of the Ontario scheme just referred to, I do not think that this is the case, but members will realize that it is difficult to make a direct comparison owing to the different money values obtaining in North America and in this country. I think that the real explanation lies in the fact that the use of electricity is a habit with most people in the United States and Canada. It has to be remembered that the United States and Canada are largely new countries where gas had not become well established when electric lighting first became available, and that the growth of most of the cities has been coincident with the electrical era. In many places both the gas and electrical interests are under the control of one company with men in high position who have rightly relegated gas to its proper function of heating purposes and reserved electricity for power and lighting. The advent of electric light into the home has been followed up by very active propaganda by salesmen of electrical accessories, while the companies have extensive showrooms in which prospective consumers can see apparatus in actual use before they commit themselves to a purchase. For instance, in Chicago the whole ground floor of the Commonwealth Edison Company's large building is used for showrooms. In these showrooms I saw, among other things, an excellent demonstration of a washing machine driven by an electrical motor, not as a special demonstration but as part of the day-by-day routine.

I do not wish to create the impression that the electric supply authorities in this country are unprogressive, but the figures that I have given show what an immensely greater business awaits them. Apart from railway electrification, which is only developing slowly, I would urge that much greater attention should be paid to securing the immense domestic load which may be as great as all the industrial business and less subject to trade fluctuations. This load is not to be secured by merely cutting the price of electricity, but it will require vigorous propaganda and salesmanship in the best sense of the word, the removal of all unnecessary restrictions, and arrangements to enable people to secure the apparatus without which they cannot use electricity. We are apt to forget that it is a feature of electrical appliances that their cost is frequently high compared with the value of the electricity which they consume in a year. To meet these points and to enable the electric supply undertakings to get some of the money which they now give to the gas companies and local merchants we must have:

(*a*) A reasonable but not necessarily a very "cut" rate for electricity.
(*b*) A system of hire or hire-purchase of the more expensive pieces of apparatus.
(*c*) In many cases, hire-purchase wiring of houses.
(*d*) A liberal practice in regard to
    (1) Laying of mains.
    (2) Showrooms.
    (3) Demonstration of apparatus.
    (4) Giving to the public what is generally known to-day as "service."

On the power side of the business in America most factories and the street, elevated, tube and high-speed interurban railways are run electrically, and there can be no doubt that with these already large loads a much bigger load awaits connection when the electrification of main-line railways really goes ahead. I hope that the electricity supply authorities in this country will see to it that they secure the supply of electricity to the railways as and when the electrification of main and suburban lines is proceeded with, so that there will be no waste of capital, and so that the load factor of the supply authorities' power stations will be improved. Immense loads are provided for the supply authorities by the local and express lift or elevator systems which are used in every important office building, and there would seem to be much room for improvement in this direction in our own country. At night, large blocks of power are used by the electrical sign advertisements, and no one who has seen the "White Way" in New York is ever likely to forget it. Despite the big power loads referred to, I was very much impressed everywhere with the steadiness of the pressure supplied to the consumers' terminals. The quality of the street lighting is also for the most part quite good and, in many important streets, the light on the road surface is equal to that in Portland-street, Manchester.

A question which is often raised, and which is sometimes difficult to decide, is whether it is better to place a generating station near the centre of gravity of the load or at some distance away and to give the supply through underground or overhead mains or, alternatively, to take a supply from an outside source, with a station at a considerable distance. In one area where hydro-electric power is used extensively, some interesting data and costs were placed at my disposal. The total cost per kWh at the power station busbars, including all capital charges, depreciation, etc., was 0·2 cent, whereas 0·35 cent per unit have to be added to this to cover all the transmission charges over a 250-mile line to the point of delivery, making a total of 0·55 cent, so that the cost of transmission is much more important

than the cost of generation. In this connection I was surprised to find that the power available from some hydro-electric systems fluctuates more than one had imagined it to do. In the area in question in the past 25 years the rainfall has varied from 10·25 to 49·45 inches per annum, and most of this rainfall occurs in only three months of the year. It follows from this that steam stations have to be employed on some parts of the system and, in one case, 30 per cent of the units sold last year were derived from the steam plant. The steam stations in California are usually supplied with oil fuel, the price of which fluctuates considerably. Were it not for this latter factor and the feared exhaustion of oil supplies, it is not unlikely that more use would be made of steam stations, especially as, at the average prices of oil, the total cost of generation on the Pacific Coast is just about the same as the cost of hydro-electric power delivered over such long lines as the one referred to.

In view of the great discussion in this country since 1914 on linking-up, etc., I shall naturally be expected to say something about the security of supply.

(*a*) A great deal of interconnection or linking-up of power systems and stations has been carried out voluntarily. Probably the outstanding example of the value of liberal linking-up was illustrated in the spring of this year, when approximately 160 000 h.p. of generating plant broke down in one week in the various stations at Niagara, and yet the interruption of supply to consumers was negligible. An ounce of practice is worth pounds of theory.

(*b*) In big cities like New York, Chicago, San Francisco and others which have local steam stations and distribution by means of underground cables, the continuity of supply is, I believe, good. In other cities which are dependent for supply on overhead transmission lines and overhead distribution networks, the supply is not by any means so good, particularly in those districts where the overhead lines are much affected by lightning and snowstorms. The effects of snowstorms and gales were particularly felt last winter in Massachusetts, Ontario, etc., as reported in the Press at the time.

Transmission and Cables.

So far as power cables are concerned, there is a good deal of experience in the United States with 24 000- and 13 200-volt, 3-core cables, and the records in the technical Press disclose that a good deal of it has not been happy. The troubles with underground cables appear to have been due both to defective manufacture and jointing and to overloading, partly under war conditions. In this connection, it has to be remembered that American engineers have mainly had to specialize in the development of overhead transmission lines, and the question of cables has been of minor importance. They are, however, now becoming much more important, and a great deal of attention is being concentrated on the development of 3-core, high-voltage cables, including those for a working pressure of 33 000 volts. The necessity for this arises out of the big loads to be transmitted and because of the attitude of the fire insurance companies towards overhead wires, especially as so many of the residences are built of wood, and because of the hindrance caused by wires to the fire brigades before they can get to work. From this it would seem that the use of underground cables will rapidly spread in the residential areas. The long transmission lines are a conspicuous feature of the electricity supply business in the United States and Canada, and in some places, owing to the absence of coal and oil, electricity must either be transmitted by them or not at all. They therefore have to be used, with their known susceptibility to lightning and storms. Troubles from these causes vary very much in different parts of the country. They are particularly bad in the Eastern and Middle West States, whereas on the Pacific Coast there is a noticeable absence of forked lightning and of snow, with the result that higher voltages are permissible there than elsewhere. It is right to add that there is abundant evidence that lightning troubles can be mitigated by the use of electrolytic and oxide-film arresters.

Transmission Pressures.

The Great Western Power Company in California is successfully operating at 165 000 volts a.c., while the Southern California Edison Company will next year, bring into use a 240-mile reconstructed line at 220 000 volts, and the Pacific Gas and Electric Company has just brought into use at 125 000 volts the Pit River–Vacaville 250-mile line which is designed for ultimate use at 220 000 volts. A great deal of the success or otherwise of transmission lines depends on the suspension-type insulators. It is notorious that these insulators were exceedingly unreliable until about five years ago and, in the interests of electricity supply generally, it is very satisfactory to know that makers in the United States and Canada, as well as one well-known firm in this country, have very seriously tackled the problem of manufacture and have developed products which can be used with confidence. In this connection I should like to say that it is my belief that insulators built to the new B.E.S.A. Specification No. 137 (1922) can be depended on for satisfactory service, but that when next the Specification is revised a high-frequency test should be added. In order to get the best practical result from such a test, it seems desirable that the wave trains should be damped so as to simulate as closely as possible those produced by lightning.

General.

I wish to take this opportunity of acknowledging the hospitality extended to me by many engineers in the States and Canada, and to express my appreciation of the handsome way in which they placed information at my disposal.

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By W. B. WOODHOUSE, Member.

(*Address delivered at* LEEDS, *7th November*, 1922.)

I have to thank you for the honour you have done me in again electing me as your Chairman, and I hope that my year of office will see not only a continuance of the growth of this Centre and of the Institution as a whole, but also a marked improvement in the general prosperity of the country.

In choosing a subject for my address I felt that I might be forgiven if I confined my remarks to matters connected with the electricity supply industry in which I am engaged. My address in 1913 * dealt with one particular problem in connection with electricity supply, namely, the conservation of coal and the possibility of a general adoption of distillation processes and the production of oils, gas and ammonia from coal, the raw material of our industry.

All our elaborate supply systems are merely a means of distributing the heat energy of coal, and the proper treatment of coal is no less important to-day than fomerly. The commercial problem is so to treat coal as to obtain the greatest difference between the selling price of the coal products and the cost of the treatment.

The disadvantages of all the processes of distillation which have been tried are, broadly speaking, two in number. First, there is the cost of the process (wages, maintenance and capital charges), and secondly, the loss of heat, or the low heat efficiency of the process. Much work has been done since I discussed this matter in 1913 and progress has been made, though commercial success has not yet been achieved.

If the growing demand for fuel oils for internal combustion engines can be met from our national coal resources, the present steady growth of the use of oil for marine purposes may be regarded with equanimity; if not, the national wealth of coal cannot so readily be used to pay the nation's debts, and the country must suffer.

The electricity supply industry is particularly fitted to take a part in the solution of this problem; coal is dealt with in large quantities, and the process of electrical power production is a continous one—conditions which are essential to any economical process of distillation. I hope that an increasing number of those engaged in electricity supply will devote their attention to this subject and will make themselves familiar with gas-works and coke-oven practice as well as with the interesting research work into the structure and composition of our coals which is taking place.

Our present practice of producing power from coal by the agency of steam and the use of boilers and turbines shows a substantial improvement on the practice of 10 years ago; larger turbines and higher steam pressures are responsible for definite savings, and boiler-house practice also has improved.

The limits of the efficient use of steam in turbines have not yet been reached, but for the moment the greatest possibility of improvement seems to lie in the boiler house. Recent developments in the use of powdered fuel are of particular interest.

It has always seemed to me a little unfortunate that the efficiency of a steam-raising device consisting of a furnace, a means of releasing heat energy, and a boiler, a means of absorbing heat energy, should not be considered in two parts, separately. If this were done there is little doubt that more attention would be directed to the furnace than has been the case in the past, and as a consequence its efficiency would be improved.

Intimately bound up with that of the economical production of power is the problem of the working of interconnected stations, a problem which, I think, will be solved in large part by a moderate amount of study. For many years we are likely to continue the use of some smaller stations during factory hours, on account of the plant already installed and of their geographical position.

To ensure the economical use of such a station as part of an interconnected system, the establishment of a controlling engineer with autocratic powers is regarded by some as essential. It should not be overlooked, however, that private steam plants exist in many cases because of the needs of their owners for steam for other purposes, and that we must provide for the interconnection of these plants as well as for the public stations. Consequently, a single control in all cases seems likely to be difficult of attainment. I am disposed to think that the control necessary for economy and reliability may be equally well obtained by the influence of tariffs based on a closer study of the costs of working, and that it will be unwise to assume that a dictatorship is the only solution.

The cost of operating any steam plant under normal conditions may be analysed very simply, and the most economical method of interworking readily arrived at. A study of the problem should enable the provision for emergency conditions also to become clearer and more obvious, and it should not be difficult by consideration and classification to provide for security as well as economy, even though the generating stations remain under separate control.

Interconnected working need not, therefore, wait upon the creation of some controlling organization, more particularly as the possibility of the use of high-pressure direct current (the adoption of which would remove many present difficulties) seems within sight.

The power-supply engineer is frequently confronted with cases where power users, because of their require-

* *Journal I.E.E.*, 1914, vol. 52, p. 30.

ments for steam for other purposes, are disposed to install exhaust or pass-out steam turbines. These cases will repay the most careful study.

The exhaust-steam turbine is sinking into a position of relative unimportance, although at one time it was a powerful buttress of the reciprocating winding engine for colliery purposes. A study of the limitations of this combination shows that it must eventually disappear, except in very special cases, in any district where a public supply system is operating from large generating stations.

Another problem is introduced by the pass-out turbine, the limitations of which are naturally rather less known than the virtues claimed for it by the makers. There are definite economic limitations to the use of this type of machine, which will repay study and which indicate that the public supply undertaking need not despair of supplying all the power requirements of works where a large amount of steam is required at low pressure for process work.

As to the transmission and distribution of energy, definite progress has been made as the result of research and experience; from the greater attention paid to this subject a much clearer knowledge is being obtained of the technical and commercial conditions to be observed. The construction and use of cables for pressures above 30 000 volts, the rating of cables, and the continued testing of their state are all problems of great interest which deserve the closest attention of the electrical industry.

As to methods of distribution, the necessity for reducing the cost is urgent. Much good would be done, I think, by a free discussion of present methods, with the object of eliminating unnecessary work and cheapening the remainder.

Many undertakings have not for many years altered their practice in the method of laying mains and making joints, and there are other details of practice which would repay consideration.

Overhead line construction is also in a state of change. New regulations governing their construction in this country will be forthcoming at an early date and the satisfaction of these regulations at minimum cost is a matter of great importance, particularly in districts where the demand for electricity is not dense. Such problems as the design of supporting poles or towers and their foundations, the properties and behaviour of conductors, copper and other metals, and of insulators of porcelain and other materials, will well repay attention. The design of service lines for distribution at the pressure of use, and the many problems arising from supply in rural districts, should all receive attention.

In connection with all these problems the records of other people's work to be found in the technical Press and in such publications as *Science Abstracts* are of great value for reference, but something more is wanted. It would, I think, be of assistance to many of us if in each principal section of electrical engineering the Institution could arrange for the publication of an annual summary of new developments and problems, such summary to be prepared by someone not only familiar with published results but in touch with the work being done by such bodies as the British Engineering Standards Association, the British Electrical and Allied Industries Research Association and the like. Such a summary would, I think, be of particular value to the younger members. The practice of electricity supply, though still changing, is in many respects becoming stereotyped; and there is a tendency for the young engineer introduced to a large and complicated supply organization to assume that existing practice is the final development. It would be unfortunate if this point of view were to lead our younger members to neglect their inventive faculties, and I feel that an annual summary such as I have referred to would prove a beneficial stimulus.

Finally, I should like to refer to the question of the relationship of supply undertakings to the public, and the necessity for making clear to the public the reasons for what are often regarded as being extraordinary tariffs. It is difficult for many non-technical people to understand why a power supply and a lighting supply should differ to such a great extent in price, and the feeling that its mystery is probably a cloak for unfair discrimination is very likely to follow. We have seen recently an agitation against the "therm" basis of charging for gas, an agitation based largely on suspicion generated in the public mind because of its unfamiliarity. To any engineer who has considered the matter, the method of charging is fully justifiable, and I have noticed with pleasure the almost complete abstention on the part of the electrical industry from the campaign against the gas companies. One should, however, learn a lesson from the gas engineers' tribulations and endeavour to make clear to the public beforehand why any particular form of tariff is adopted, so that public confidence may not be lost.

This problem of equitable tariffs becomes of more importance as a supply is given over wider and less thickly populated areas. The Hopkinson basis of charges was a sufficient approximation for supply in a densely populated area, but no tariff based only on a demand charge plus a unit charge can equitably be made to fit all the circumstances in an area including town and country districts. It is necessary to declare frankly that the cost of distribution must make the charges for electricity higher in rural districts, and I think that the whole industry would be helped by a general discussion of this subject.

The work of the Institution and the Electrical Development Association in this respect is helpful, and we are, as an industry, fortunate in having the Electricity Commissioners to stand between us and an uninstructed agitation such as has been directed against the gas industry.

Progress in supply, whether under the management of a company or a municipality, can only be maintained subject to the essential economic condition of a fair return on capital and a reasonable margin to permit developments to be made by research or enterprise, so that the industry may be kept in the forefront of progress and be active and healthy enough to meet changed conditions in the interests of all concerned

I believe that any concerted action of the industry has been much retarded by the antagonism which has existed in the past between various sections. I am glad to think that the work of the Electricity Commissioners in the co-ordination of supply, the

avoidance or adjustment of overlapping powers, and the general and wide supervision which they have of the developments of electricity supply, has already done good, and that the settlement at an early date of the respective spheres of operation and the association together of electricity undertakings will permit both municipal and company engineers to co-operate as never before, without feeling that political advantage will be taken of their mutual confidence.

Many of these problems are in particular for the younger men of our industry to solve; their solution is necessary not only for the prosperity of the electricity supply industry, but in the interests of the country as a whole.

In recent years the industry has been relatively prosperous; it can only remain so by an appreciation of national needs, by hard work and by close co-operation on the part of all concerned.

EAST MIDLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By WILLIAM PEARSON, Associate Member.

(EXTRACT *from Address delivered at* LOUGHBOROUGH, 10*th October*, 1922.)

The changes which take place gradually among our daily associations tend to pass unnoticed, and it is well sometimes to attempt to realize the changes over a considerable period to determine whether the altered circumstances necessitate a new attitude towards them. As a rule these scarcely perceived changes of conditions will have resulted in an unconscious adjustment, but one inadequate to make the best of the new situation.

The genius of the British people is individualistic, and this quality, with the self-reliance and initiative associated with it, was entirely advantageous while the electrical industry was in the experimental stage. But when an industry reaches the stage of quantity production of articles of established types, the advantage tends to lie with the large manufacturing corporations which are characteristic of other countries. The remedy may be in similar large aggregations of capital and manufacturing plant, but (despite some successful examples of this kind) I believe that the engineering industry of this country will continue to be largely in the hands of companies of smaller size. The alternative is to be found in co-operative action to secure for the common good those advantages which cannot be efficiently attained by the isolated efforts of individual firms. There is also a large sphere in which the user could and should co-operate with the manufacturer for the good of the industry as a whole. It is with the idea that such co-operation should be more deliberately encouraged that I am taking this opportunity to call attention to some of the forms of co-operation which have already emerged.

Co-operation is the chief condition of progress in human society. The stimulus of competition is valuable only in so far as it leads to co-operation, and apart from this result its benefits are short-lived. Unrestricted competition results in the inefficient use of the ability employed in the industry as a whole, in crippled financial resources, and in deterioration of the product. In the world of sport everyone realizes that combination is the first essential, and there is no doubt that if, in industry, means could be found to secure whole-hearted co-operation between labour, capital and management, production would be enormously increased. Much might be said with regard to the efforts made during the past few years to secure such co-operation, but I propose to limit my remarks to the benefits resulting from co-operation between the manufacturers engaged in the engineering industry and those who represent the purchaser of the product.

This Institution has taken a leading part in one matter, not of a technical character, which will serve as an illustration—I refer to General Conditions of Contract. In the past, some of those acting on behalf of purchasers regarded the contractor not as an ally in securing the achievement of the purpose of the contract, but as an opponent to be taken at a disadvantage by the aid of very one-sided General Conditions. The position became so intolerable that in 1911 a number of manufacturers came together and agreed to insist upon three protective clauses being inserted in all contracts. Out of such action developed the British Electrical and Allied Manufacturers' Association, which has since standardized sets of general conditions applicable to all kinds of contracts and fair to both parties. But the work of the Institution in producing its more elaborated Model General Conditions of Contract in 1912 (with subsequent revisions) owes its value to the fact that it represents collaboration between all the interested parties. The use of these conditions not only removes the cause of much friction, but also saves the almost incredible amount of time which previously was wasted in the study of conditions that differed in almost every contract. In this matter the engineers appear to be pioneers, and the Federation of British Industries, which is at present

investigating the possibility of producing general conditions applicable to industry generally, will probably find their best model in the I.E.E. Model General Conditions of Contract.

The revision of the I.E.E. Wiring Rules, which is at present in progress, is another example of an important matter in which all the organizations interested are participating.

Other collaborations of similar type but more limited scope are those between the Incorporated Municipal Electrical Association and the British Electrical and Allied Manufacturers' Association, dealing with standard schedules of guarantee and performance, etc., in relation to turbo-generator and condensing-plant contracts.

In passing, it should be noted that the Institutions themselves represent a form of co-operation between individual engineers, and that the need for further co-operation has led to the proposal of a Joint Council for the four premier Institutions, and to an endeavour to form an Association of British Engineering Societies to co-ordinate the work of a large number of other technical organizations.

The function of the engineer may be defined as "the economy of human effort," and in support of this one need only mention transport by land and sea, or the application of power to all kinds of manufacture. Yet it is probable that the number of non-producers in engineering is at least as large proportionately as in other industries. There seems to be no immediate prospect of any serious reduction in the large army of workers engaged in the distribution of goods made by other people, but a small effort in this direction is the co-operative publicity work which is the function of the British Electrical Development Association, a development of the Heating and Cooking Committee of this Institution, and the result of the collaboration of seven other Associations with the Institution.

The most important of these endeavours to secure efficiency in the industry by the combined efforts of all interested parties relate, however, to research and standardization, and I wish to direct your attention particularly to these subjects.

(Mr. Pearson then referred to the research work fostered by the Committee of the Privy Council for Scientific and Industrial Research, and described in detail the organization and work of the British Electrical and Allied Industries Research Association. He also described the origin, purpose and methods of the organizations concerned with standardization, i.e., the British Engineering Standards Association and the International Electrotechnical Commission. He quoted the official B.E.S.A. statement that "Industrial standardization has for its main objects the elimination of the waste of time and material involved in the production of a multiplicity of sizes and qualities for one and the same purpose, the fixing of dimensions of component parts where interchangeability is essential, the setting up of standards of performance whereby comparisons can be made with equity, and the defining of attainable quality of material." He indicated various kinds of standardization fulfilling these different objects, and then made special reference to the Rating of Electrical Machinery, describing the recent revision of British Standard Specification No. 72 as being the most important in relation to electrical engineering. He showed how the several Specifications shortly to be issued would adequately meet the needs of the industry, which the superseded document failed to do, and urged it as a duty to make the fullest possible use of these Specifications when available.)

THE PRODUCTION OF NOISE AND VIBRATION BY CERTAIN SQUIRREL-CAGE INDUCTION MOTORS.*

By F. T. CHAPMAN, D.Sc., Member.

(*Paper received* 3*rd April*, 1922.)

SUMMARY.

(1) A suggestion is made that the high-pitched notes emitted by some induction motors are due to a side-pull arising from an unsymmetrical field which may be produced when certain numbers of rotor slots are used.
(2) A simple case is first considered and the dissymmetry shown.
(3) and (4) The forces produced are indicated and their effects considered.
(5) The field is analysed and found to include pairs of components, such that in each pair the numbers of poles differ by two. The interferences between such pairs of fields produce the effects observed.
(6) An elementary investigation is made which gives an expression for the frequency of the note produced.
(7) Illustrative examples are considered.
(8) The principle is extended.
(9) A more general investigation is made.
(10) A rule is developed for determining what numbers of rotor slots should be avoided.
(11) Some experimental results are given.

(1.)

Induction motors with squirrel-cage rotors usually have excellent characteristics as regards efficiency, power factor and robustness, while a high starting torque is not expected of them, in general. The rotor is extremely simple, but in spite of this simplicity it presents one or two minor, though intricate, problems in connection with the choice of the number of slots. In order to secure a high power factor at full load and a large pull-out torque it is desirable to employ a large number of slots per pole, say 10 or more, but such a rotor may exhibit a tendency to crawl at or about certain sub-multiples of synchronous speed, viz. in the case of a three-phase motor, 1/7th, 1/13th, etc., of full speed. This tendency to crawl can be sufficiently prevented (*a*) by adopting suitable fractional-pitch windings in the stator, and (*b*) by skewing the rotor slots through one stator slot-pitch. There are cases, however, where these remedies cannot be applied and where crawling is guarded against by using a suitably chosen number of slots less than the number in the stator. Such rotors have the additional advantage that they are cheaper to construct than those having larger numbers of slots.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

Considerable care is necessary in choosing the number of slots in the latter case, as such rotors are liable to be very noisy in starting and on load, they may exhibit a tendency to crawl at speeds higher than those mentioned above, and they may give rise to serious vibration. Experienced designers are familiar with certain numbers of slots which are safe, but, so far as the author knows, the matter has never been very fully investigated nor have any reliable rules been published. Most manufacturers have trouble from this source from time to time, but direct experimental investigation is not possible on account of the large expense involved in testing a sufficiently great number of combinations of numbers of poles, and of rotor and stator slots. A motor which has the defects mentioned may produce a fairly high-pitched musical note at speeds within a certain range, and the intensity of the sound may reach a maximum near the middle of the range. In some cases there are several noisy speed-ranges and full-load speed may come within one of them, although a motor which is very noisy at one point during the starting period may operate quite quietly at full speed. When the maximum effect is felt at some speed during the starting period, the vibration may be sufficiently severe to introduce a considerable retarding torque due to friction at the bearings and also, perhaps, to the currents induced in the rotor by its peculiar motion in the field, and the remaining torque may be zero or insufficient to accelerate the machine further.

These effects are probably due to unbalanced magnetic fields, arising as indicated below, which produce rotating forces similar to those caused by mechanical unbalance; the speed of rotation of these forces is much higher than that of the rotor itself, so that the critical speed of the rotor is reached and exceeded even in moderate-speed machines.

(2.)

It is convenient to commence by studying a definite, simple case and we will consider a rotor with five slots acted on by a four-pole, sine-shaped rotating field. We shall neglect the slot openings and assume that the rotor is surrounded by a uniform air-gap.

Fig. 1 shows the relative positions of rotating field and rotor conductors at a certain instant. The teeth are numbered and the arrow indicates the direction of motion of the field with respect to the rotor, the latter being supposed at rest. Positive ordinates indicate flux entering the rotor. It is clear that all the rotor conductors will experience the same virtual E.M.F. and they will all have the same inductance and

resistance, hence the virtual current and the angle of lag will be the same for all. The phase difference between the E.M.F.'s or currents in successive conductors is $4\pi/5 = 144°$. The vector diagram in Fig. 2 refers to the same instant as Fig. 1, and the full lines represent the E.M.F.'s in the rotor conductors. The vector marked (5, 1) refers to the conductor in the slot between tooth No. 5 and tooth No. 1. In this investigation we shall neglect the resistance of the conductors, so that the current will lag 90° behind the E.M.F. in all cases. On this assumption the current vectors are shown in Fig. 2 by broken lines.

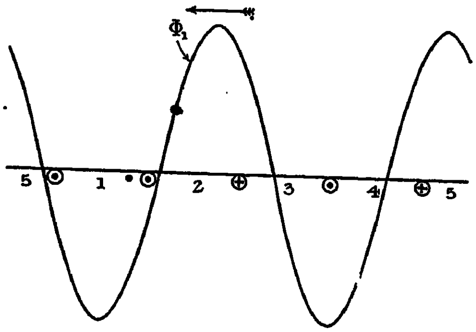


FIG. 1.

Now, the conductors are short-circuited at each end by rings, which rings are not connected together by any other path, therefore the sum of the five currents must be zero at every instant. This means that the vectors representing them must form a closed polygon when taken in the same order as the slots. This polygon is

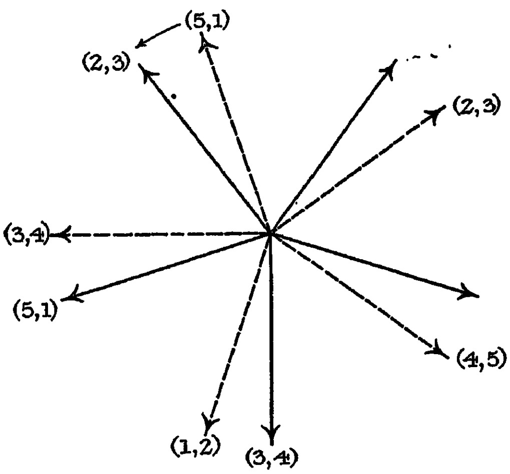


FIG. 2.

drawn in Fig. 3 and is so numbered that the vector (5, 1) represents the current in the conductor between tooth No. 5 and tooth No. 1, and so on. These rotor currents produce a magnetic field which combines with the original four-pole field and produces a very irregular resultant. We shall assume that the effects of saturation and of the slot openings can be neglected, and in the first place we shall examine the form of the field which the rotor currents would produce if they acted alone.

It is a well-known proposition that the M.M.F. acting on the air-gap opposite tooth 5 differs from that acting opposite tooth 1 by the M.M.F. due to the current in conductor (5, 1); hence, if 0 be the centre of the circumscribing circle in Fig. 3, the vectors (0, 1), (0, 2), (0, 3), etc., will represent the maximum ampere-turns acting on the air-gap opposite teeth Nos. 1, 2, 3, etc., respec-

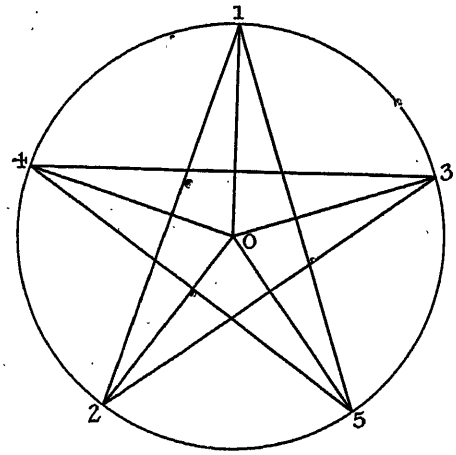


FIG. 3.

tively, to the same scale as (5, 1), (1, 2), etc., represent the maximum current per conductor. This follows because the vector (5, 1) is the difference between the vectors (0, 5) and (0, 1), and because the algebraic sum of the instantaneous values of the fluxes in all the teeth must be zero at every instant. With the aid of Fig. 3 we can draw the stepped curve of Fig. 4 (abcdefghkl) which shows the distribution of the field, Φ_2, due to the rotor currents at the instant

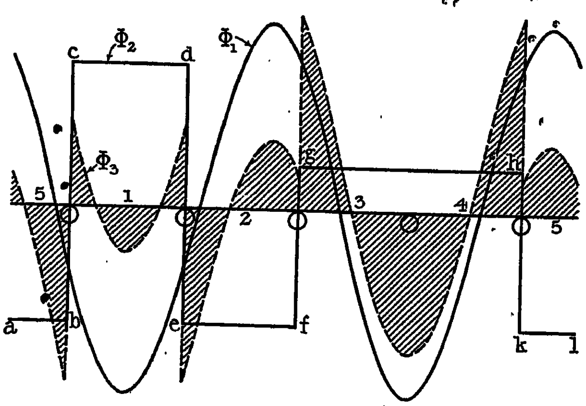


FIG. 4.

when the flux in tooth 1 is at its maximum value. It will be seen that a kind of four-pole field is produced which satisfies the condition that the total flux entering the rotor is equal to the total flux leaving it.

The curve Φ_1 shows the position of the main flux wave at this instant. The curve Φ_3 which bounds the shaded areas is obtained by adding together at each point along the rotor surface the ordinates of curves Φ_1 and Φ_2. The values of the rotor currents and fluxes have been calculated on the assumption that the end

leakage may be neglected. The formulæ employed were those given by the author in a paper on "The Air-gap Field of the Induction Motor," * and they indicate that the maximum height of the stepped curve is 0·757 times the height of the Φ_1 curve. A useful check on this figure is provided by the fact that, since the rotor conductors are assumed to have no resistance, the net flux traversing any tooth must be zero at every instant, a condition which the curve Φ_3 fulfils.

(3.)

Now the force with which any element of the rotor surface is attracted towards the stator is proportional to the square of the flux density at that point. The circle in Fig. 5 represents the rotor of the previous figures, the conductors being shown and the teeth numbered. Outside the circle radial lines have been drawn, the lengths of which are proportional to the squares of the resultant densities (Φ_3) shown in Fig. 4.

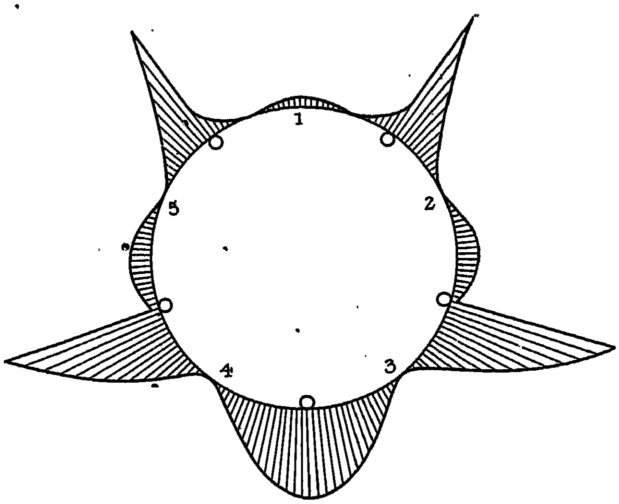


FIG. 5.

It is clear from this diagram that the rotor experiences a resultant force directed radially outwards through the centre of slot (3, 4).

Fig. 6 has been drawn to show the flux distribution 1/10th cycle later when Φ_1 has moved through 1/20th revolution and the vectors of Figs. 2 and 3 have moved through 1/10th revolution. The resultant field is similar to that of Fig. 4, except that it is moved one slot to the right and reversed in sign. If a new figure corresponding to Fig. 5 were drawn for this case it would be found that the resultant force had the same value as before, but was now directed outwards between tooth No. 4 and tooth No. 5, hence in 1/10th cycle its direction has turned through 1/5th revolution. Further diagrams drawn in the same way would show that the force vector makes two revolutions per cycle and therefore rotates four times as fast as Φ_1, relatively to the rotor.

(4.)

This unbalanced force tends to bend the shaft of the rotor and under steady conditions, the plane of the neutral axis will rotate at the same speed in space as the unbalanced force; this speed is quite different from the speed of rotation of the rotor, if any. The shaft being bent, the air-gap is reduced on one side and an increased unbalanced magnetic attraction is produced, which is added to the original disturbing force, and further, since the centre of gravity of the rotor is whirling with the neutral axis in a circle, a centripetal mass-acceleration is required to maintain the motion. Steady motion is obtained when the shaft is bent to such an extent that the elastic forces set up by the bending are just sufficient to balance the magnetic attraction and to provide the requisite mass-acceleration. It should be noted that such steady conditions cannot exist while the rotational speed of the rotor is changing, because the frequency of the forces brought into play is changing continuously.

The forces acting on the stator and rotor due to magnetic unbalance are equal and opposite, and therefore are balanced if the motor is regarded as a whole, but it is otherwise with the mass-acceleration, which leads to reactions at the bearings that are transmitted to the foundations, producing the same effects as regards

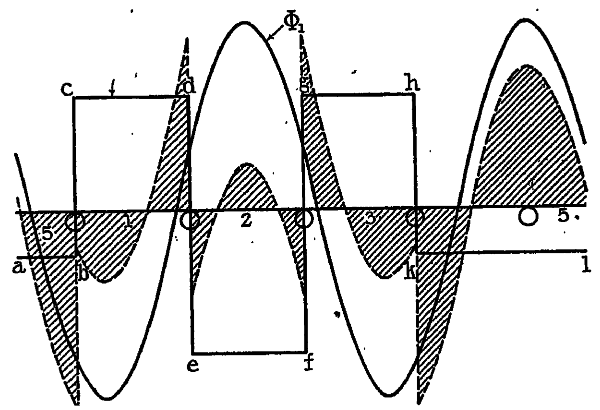


FIG. 6.

noise and vibration as if the rotor were mechanically out of balance and were rotating at the speed at which it now whirls. We shall see later that conditions may exist in a motor which cause the frequency of these forces to be that of a high-pitched musical note, and therefore comparatively small forces (i.e. small deflections) will cause a loud noise. It will also be obvious from the dynamics of the problem that with a given initial disturbing force there will be a certain speed of rotation of this force at which the deflection of the shaft becomes unstable and stator and rotor may come into contact with one another. From the examples given below we shall see that, as the rotor accelerates, the speed of the disturbing force varies over a very wide range, and the critical whirling speed to which we have just referred (which is practically identical with the mechanical critical speed) may be included within this range; the vibration may then be so severe that further acceleration is prevented. Thus we get a crawling speed of a new kind, which is necessarily accompanied by loud noise and vibration.

The action of the main magnetic field under these

* *Electrician*, 1916, vol. 77, p. 663.

circumstances is somewhat obscure, since the presence of the closed squirrel-cage winding prevents rapid changes in the flux distribution, which might otherwise be caused by the whirling. It may be expected, however, to flatten out the resonance curve to a considerable extent and to damp the whirling. It will be clear that if two motors which are otherwise identical have shafts with different degrees of stiffness, the one with the more rigid shaft is less likely to give trouble than the other. Any looseness in the bearings, between the rotor and the shaft or between the stator and its housing, would accentuate the effects here discussed. It may be possible for a given combination of stator and rotor slots to be troublesome in one case and to have little effect in another.

(5.)

The method of investigation which has been given in Section 2 is too laborious for general use, and a further analysis is necessary in order to establish rules to indicate how these effects may be avoided.

A useful light is thrown on the phenomenon if we apply Fourier's analysis to the fields shown in Figs. 4 and 6. In the paper * referred to above, the author

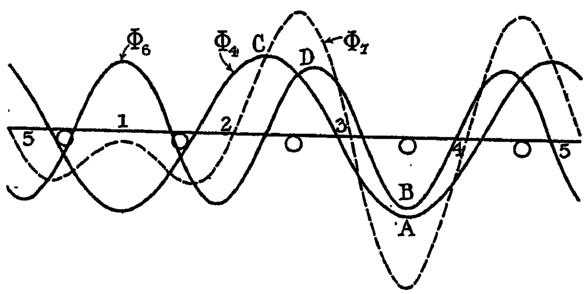


FIG. 7.

has shown that if an inducing field having p poles acts on a squirrel-cage rotor winding with G conductors the fields produced by the rotor currents can be resolved into a series of fields, each of which has cp poles, and may rotate in the same direction as the original field, or in the opposite direction with respect to the rotor. The possible values for c form an infinite series and the general term is given by the expression

$$c = \frac{2Gd}{p} + 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where d is any positive or negative integer. Those fields for which c is negative rotate in the opposite direction to the original field, the others in the same direction. The speeds of the fields are such that they all produce E.M.F.'s of the same frequency, in phase with one another, in any rotor conductor.

Formula (1) can be written

$$cp = 2Gd + p \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The amplitude of any one of these fields is equal to

$$\frac{2G \sin (cp\pi/2G)}{cp\pi} \times y$$

* Loc. cit.

where y is the maximum density in the air-gap opposite any tooth, as determined from such a vector diagram as that given in Fig. 3.

If we consider the case of Section 2 in which $G = 5$ and $p = 4$, and substitute successively in Equation (2) the following values for d, viz. 0, -1, $+1$, -2, $+2$, etc., we get the following as the numbers of poles in the series of multiple fields that are present,

$$cp = 4, \ -6, \ 14, \ -16, \ 24, \text{ etc.}$$

The important point about this series is that it consists of a number of pairs of oppositely rotating fields in which the numbers of poles differ by two, thus (4, $-$ 6), (14, $-$ 16), etc.

In Fig. 7 the curve Φ_4 represents the difference between Φ_1 and the four-pole component of Φ_2, a flux wave which moves, like Φ_1, from right to left; Φ_6 represents the six-pole component of Φ_2 and moves from left to right. Φ_7 represents the resultant of these two fields at a certain

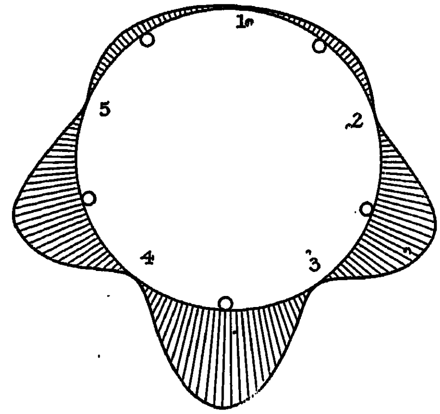


FIG. 8.

instant, and the corresponding force diagram is shown in Fig. 8. Figs. 7 and 8 show the characteristic feature of the resultant field produced by combining a p-pole field with a $(p \pm 2)$-pole field, viz. that there is a strong zone the centre of which is immediately opposite to that of a weak zone, which leads to an unbalanced magnetic pull. This force can be represented by a radial vector rotating about the axis of the rotor.

If a p-pole field be combined with a $(p + x)$-pole field, where $x = 4$, 6, 8, 10, etc., there will be $x/2$ strong and $x/2$ weak zones distributed regularly round the periphery of the rotor, and the forces will constitute a balanced system. It is only when $x = 2$ that unbalanced forces arise.

(6.)

The speed at which the force vector rotates can be determined in the following manner. Suppose we have a p_1-pole field rotating at n_1 revs. per sec., and a p_2-pole field rotating at n_2 revs. per sec. If $p_2 = p_1 + 2$, then interference effects will be produced as shown above. When a crest of the p_1-pole field coincides with a crest of the p_2-pole field, as shown in Fig. 7 at A and B, the force vector is directed outwards through the corresponding point on the rotor, viz. slot (3, 4). We will take a movement from right to left as positive. At

a certain instant, earlier or later than that of Fig. 7 according to the direction of relative motion of the two fields, the crests C and D will coincide and the force vector will have moved to this new point of coincidence. The speed of the p_2-pole field with respect to the p_1-pole field is $(n_2 - n_1)$ revs. per sec. Relatively to the p_1-pole field the force vector will have moved from A to C, i.e. through $1/p_1$th of the circumference, while the p_2 field moves through $(1/p_1 - 1/p_2)$th of the circumference, hence the velocity of the force vector relative to the p_1-pole field is greater than the relative velocity of the p_2-pole field in the ratio

$$1/p_1 : (1/p_1 - 1/p_2)$$

therefore the speed of the force vector relative to the p_1-pole field is

$$\begin{aligned}(n_2 - n_1) \times \frac{1/p_1}{1/p_1 - 1/p_2} \\ = \frac{(n_2 - n_1)p_2}{p_2 - p_1} \\ = \tfrac{1}{2}[(n_2 - n_1)p_2] \quad . \quad . \quad . \quad . \quad (4)\end{aligned}$$

Now the speed of the p_1-pole field is n_1, so that the speed of the force vector in space is

$$\begin{aligned}n_1 + \tfrac{1}{2}[(n_2 - n_1)p_2] \\ = \tfrac{1}{2}[n_2p_2 - n_1(p_2 - 2)] \\ = \tfrac{1}{2}(n_2p_2 - n_1p_1) \quad . \quad . \quad . \quad . \quad (5)\end{aligned}$$

If either of these fields is produced by the direct magnetizing effect of the stator currents, its speed is known from the relation $np = 2f$, where f is the primary frequency; but if one or both arise from rotor currents the speeds must be calculated as follows. Suppose a p_4 field is produced by rotor currents which are induced by a p_3 stator field, then

$$(\pm)p_4 = 2Gd + p_3 \quad . \quad . \quad . \quad . \quad (6)$$

If the speed of the p_3 field is n_3 and that of the rotor n_0, the frequency of the rotor currents under consideration is

$$(n_3 - n_0)p_3/2 \quad . \quad . \quad . \quad (6a)$$

n_3 must here be given its proper sign, whilst p_3 is taken as a positive quantity.

(The difference between a positive and a negative frequency is expressed in the difference in phase sequence of the currents in the rotor bars. For example, in order to produce the same frequency in this sense, the four-pole and six-pole fields of Fig. 7 must rotate in opposite directions with respect to a five bar rotor, whereas if both rotated in the same direction the frequencies of the E.M.F.'s produced would differ in sign.)

The speed of the p_4 field relative to the rotor is such that the frequency of the E.M.F.'s which it induces in the rotor conductors is the same as the frequency due to the p_3 field, i.e.

$$(n_4 - n_0) \times (\pm)\, p_4 = (n_3 - n_0)p_3 \quad . \quad . \quad (7)$$

hence $$n_4 = n_0 + (n_3 - n_0)p_3/(\pm)p_4 \quad . \quad . \quad . \quad . \quad (8)$$

or, to avoid ambiguity of sign, we may write

$$\begin{aligned}n_4 = n_0 + \frac{(n_3 - n_0)p_3}{2Gd + p_3} \\ = \frac{2Gdn_0 + n_3p_3}{2Gd + p_3} \quad . \quad . \quad . \quad . \quad (9)\end{aligned}$$

n_4 may be either positive or negative, and when required for substitution in Equation (5) as n_1 or n_2 it must always be associated with its proper sign; on the other hand, when p_4 is used in this equation as p_1 or p_2 it must be taken as a positive quantity; the examples given in Section 7 will help to make this point clear.

Since the force acting on each element of the rotor surface depends on the total induction density there, this method of singling out two components of the field and considering them apart from the rest requires some justification; it explains the phenomena clearly and correctly, but it does not constitute a sufficiently rigorous treatment of the problem. A more general treatment is given in Section 9, where it is shown that an unbalanced force can only arise when there are component fields with numbers of poles differing by two, and that the magnitude of this force is proportional to the product of the amplitude of these two components.

(7.)

Some numerical examples will serve to illustrate the matter.

Example (1). *A four-pole, 50-period three-phase motor has a squirrel-cage rotor with 19 slots; the fifth multiple field of this machine has 20 poles and runs backwards at a speed which is one-fifth of that of the main field, i.e. at -5 revs. per sec.*—From Equation (2) we see that the rotor currents induced by this field produce a series of fields the numbers of poles in which are

$$20, \ -18, \ 58, \ -56, \text{ and so on,}$$

a series of pairs of numbers differing by two in each case. We will consider the first pair in which

$$p_3 = 20 = p_2, \text{ and } p_4 = 18 = p_1, \ (d = -1)$$

Case (*a*).—If the rotor is stationary we have $n_0 = 0$

$$n_3 = n_2 = -5, \text{ and } n_4 = n_1 = \frac{0 - 5 \times 20}{-18}$$

[from Equation (9)]

$$\begin{aligned}n_2p_2 = -5 \times 20 = -100 \\ n_1p_1 = +5 \times 20 = +100\end{aligned}$$

hence the speed of the force vector, by Equation (5), is

$$\frac{-100 - 100}{2} = -100 \text{ revs. per sec.}$$

Case (*b*).—At synchronism, $n_0 = 25$ revs. per sec.

$$\begin{aligned}n_3 = n_2 = -5 \\ n_4 = n_1 = \frac{-2 \times 19 \times 25 - 5 \times 20}{-18} = \frac{1\,050}{18}\end{aligned}$$

hence the speed of the force vector is

$$\frac{-5 \times 20 - 1\,050}{2} = -575 \text{ revs. per sec.}$$

This speed corresponds to a fairly high musical note. Between standstill and full speed the force vector will probably have passed through the critical speed of the rotor.

Example (2). *A four-pole, 50-period three-phase motor*

has a squirrel-cage rotor with 29 *slots. The seventh multiple field of this machine has* 28 *poles and its speed is* + 3·57 *revs. per sec.*—The numbers of poles in the components of the field set up by the rotor currents induced by the seventh stator field are, by Equation (2)

28, − 30, 86, − 88, etc.

Case (*a*).—When the rotor is stationary, $n_0 = 0$. Considering the first pair of fields, we have

$$p_3 = p_1 = 28\,;\; p_4 = p_2 = 30,$$
$$n_3 = n_1 = 3\cdot 57,$$
$$n_4 = n_2 = \frac{0 + 3\cdot 57 \times 28}{-30}, \text{ (since } d = -1)$$

The speed of the force vector is

$$\frac{-3\cdot 57 \times 28 - 3\cdot 57 \times 28}{2} = -100 \text{ revs. per sec.}$$

Case (*b*).—At synchronism, $n_0 = 25$ revs. per sec.

$$n_3 = n_1 = 3\cdot 57$$
$$n_4 = n_2 = \frac{-58 \times 25 + 3\cdot 57 \times 28}{-30} = \frac{1\,350}{30}$$

The speed of the force vector is

$$\frac{1\,350 - 3\cdot 57 \times 28}{2} = 625 \text{ revs. per sec.}$$

Between standstill and synchronism there is obviously some speed of the rotor at which the force vector is stationary. This speed can be determined from the equations given above, and is 3·45 revs. per sec. The magnitude of the force at this speed, however, is extremely small.

(8.)

In the two cases considered in Section 7 the rotor currents themselves give rise to pairs of fields which interfere with one another and produce the magnetic "beats" which cause the rotating side pull, but there are cases of another kind in which a field produced by the stator currents interferes with an entirely independent one produced by the rotor currents. For instance, if a four-pole, three-phase motor has a squirrel-cage rotor with 25 slots, the currents induced in the rotor bars by the main field will produce a complex field with components having

4, − 46, + 54, etc., poles.

The − 46 field interferes with the 11th multiple field of the stator which has 44 poles. If the stator should have 24 slots the 11th field would be very important, especially if the slots were open rather wide, in which case its amplitude at full load might exceed that of the main field. On the other hand, the currents induced in the rotor winding by the 11th stator field produce a complex field the components of which have

44, − 6, 94, − 56, etc., poles.

The (− 6)-pole field is the most important of this series; its amplitude is greater than that of the 44-pole field, and it produces interference effects with the main field of the motor. The force vectors corresponding to these two sets of "beats" rotate at the same speed, but in general they differ in magnitude and in phase. and produce a resultant. If the frequency of supply were 50 periods per sec. and the motor were running with 20 per cent slip, the speed of the force vectors would be 560 revs. per sec.

A 25-slot rotor in a four-pole motor produces a large number of other sets of interfering fields and so has a great capacity for producing noise.

(9.)

GENERAL EXPRESSION FOR THE RADIAL FORCES ACTING ON A ROTOR.

Let the circle of Fig. 9 represent an end view of the periphery of a rotor, round which a complex field exists. In a perfectly general case the induction density at

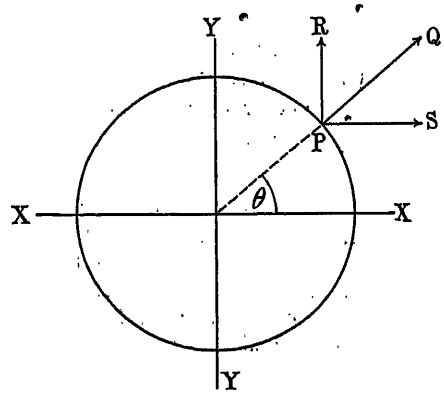


FIG. 9.

any point P on the surface of the rotor is given by the expression

$$A \sin(\theta + a) + B \sin(2\theta + b) + C \sin(3\theta + c) + \ldots$$

The radial force PQ acting on an element of the surface measuring $\delta\theta$ tangentially and of unit length axially is given by the expression

$$K\,\delta\theta\,[A \sin(\theta + a) + B \sin(2\theta + b) + C \sin(3\theta + c) + \ldots]^2$$

where K is a numerical coefficient.

In order to examine to what extent the forces on all the elements of the surface are balanced we will resolve PQ into its components

$$PR = PQ \sin\theta = K[A \sin(\theta + a) + B \sin(2\theta + b) + \ldots]^2 \sin\theta\,\delta\theta \quad (10)$$

and

$$PS = PQ \cos\theta = K[A \sin(\theta + a) + B \sin(2\theta + b) + \ldots]^2 \cos\theta\,\delta\theta \quad (11)$$

Case (*a*). *Permeance of air-gap uniform.*—K is now a constant and by integrating expression (10) between $\theta = 0$ and $\theta = 2\pi$ we get a value for the unbalanced

force in the direction of the y-axis, while the integration of (14) gives the unbalanced force in the direction of the x-axis.

These integrations furnish a first series of terms such as

$$K\int_0^{2\pi} N^2 \sin^2 (\nu\theta + n) \sin\theta\, d\theta$$

and $$K\int_0^{2\pi} N^2 \sin^2 (\nu\theta + n) \cos\theta\, d\theta, \text{ respectively}$$

the values of which are all zero, and a second series of terms such as

$$K\int_0^{2\pi} 2MN \sin (\mu\theta + m) \,.\, \sin (\nu\theta + n) \sin\theta\, d\theta$$

and

$$K\int_0^{2\pi} 2MN \sin (\mu\theta + m) \,.\, \sin (\nu\theta + n) \cos\theta\, d\theta, \text{ respectively,}$$

where ν is greater than μ.

The first of these becomes

$$NMK\int_0^{2\pi} \cos [(\mu - \nu)\theta + (n - m)] \sin\theta\, d\theta$$
$$- NMK\int_0^{2\pi} \cos [(\mu + \nu)\theta + (n + m)] \sin\theta\, d\theta$$

which develops into

$$\tfrac{1}{2}NMK\int_0^{2\pi} \sin [\theta + (\mu - \nu)\,\theta + m - n] d\theta$$
$$- \tfrac{1}{2}NMK\int_0^{2\pi} \sin [\theta - (\mu - \nu)\theta - (m - n)] d\theta$$
$$- \tfrac{1}{2}NMK\int_0^{2\pi} \sin [\theta + (\mu + \nu)\theta + n + m] d\theta$$
$$+ \tfrac{1}{2}NMK\int_0^{2\pi} \sin [\theta + (\mu + \nu)\theta - m - n] d\theta$$

Since μ and ν are both positive integers and ν is greater than μ, the last three terms are all zero. The first term is also zero except in the one case where $\nu - \mu = 1$; its value is then

$$PR = \pi NMK \sin (m - n)$$

Similarly the cosine component, PS, is

$$\pi NMK \cos (m - n)$$

when $\nu - \mu = 1$, and is zero in all other cases. The resultant unbalanced force, PQ, is πMNK and is inclined to the x-axis at an angle $(m - n)$.

Thus we see that if the actual field can be resolved into components two of which have numbers of poles, 2μ and 2ν, which differ by 2, these two fields will cause a resultant radial force to act on the rotor. In a perfectly general case it is conceivable that there might be a number of such pairs of fields, the effects of which might cancel one another, but in the induction motor, such pairs only occur in the special circumstances investigated above.

In the induction motor the components of the field are rotating at various speeds, and therefore n and m are functions of the time. If we suppose the μ field to be rotating with angular velocity ω_1, and the ν field with angular velocity ω_2, then

$$m = - \mu\omega_1 t + m'$$
and $$n = - \nu\omega_2 t + n'$$
hence $$m - n = m' - n' + (\nu\omega_2 - \mu\omega_1)t \quad . \quad . \quad (12)$$

The instantaneous components of the unbalanced force are

$$PR = \pi NMK \sin [(\nu\omega_2 - \mu\omega_1)t + (m' - n')] \quad . \quad (13)$$
and $$PS = \pi NMK \cos [\nu\omega_2 - \mu\omega_1)t + (m' - n') \quad (14)$$

which indicate a constant force of magnitude proportional to the product of the amplitudes of the two fields, applied to the rotor in a direction which rotates with an angular velocity of $(\nu\omega_2 - \mu\omega_1)$ radians per sec.

Each pair of fields with numbers of poles differing by two will produce such a rotating force, but in the practical case the resulting forces differ in magnitude and in relative position, and generally they cannot cancel one another.

The speed of the rotating force in revs. per sec. is

$$\nu\frac{\omega_2}{2\pi} - \mu\frac{\omega_1}{2\pi}$$

and, since $\nu = \tfrac{1}{2}p_2$ and $\mu = \tfrac{1}{2}p_1$, this expression is identical with Equation (5).

Case (*b*). *Variable permeance.*—When the permeance of the air-gap varies periodically owing to the presence of slot apertures, etc., K is not constant but varies in a regular manner from a maximum to a minimum and back again to a maximum. If we suppose the effect to be due to the slot openings of the rotor only, the permeance will have G maximum and G minimum values. Let us consider G points on the circumference at each of which the permeance will have the same value. For each point we shall have a pair of expressions such as (13) and (14) above. Taking first expression (13) and assuming θ to be measured from one of the G points, we get a series of expressions for the sine components of the forces acting at the several points, such as

$$K[A \sin a + B \sin b + \ldots N \sin n \ldots]^2 \sin 0 \,.\, \delta\theta$$
$$K[A \sin (2\pi/G + a) + B \sin (4\pi/G + b) + \ldots$$
$$+ N \sin (2\nu\pi/G + n) + \ldots]^2 \times \sin (2\pi/G) \,.\, \delta\theta$$
etc.

The $(R + 1)$th expression is

$$K[A \sin (2\pi R/G + a) + B \sin (4\pi R/G + b) + \ldots$$
$$+ N \sin (2\nu\pi R/G + n) + \ldots]^2 \sin (2\pi R/G) \,.\, \delta\theta$$

Each of these G expressions contains similar terms to those set out for the $(R + 1)$th. Expanding the $(R + 1)$th expression we obtain two series of terms such as

$$KN^2 \sin^2 (2\nu\pi R/G + m) \,.\, \sin (2\pi R/G) \,.\, \delta\theta \quad . \quad . \quad (15)$$
and
$$2KMN \sin (2\mu\pi R/G + m) \,.\, \sin (2\nu\pi R/G + n)$$
$$\sin (2\pi R/G) \,.\, \delta\theta \qquad (16)$$

When we add together the expanded expressions for all the G components, we find that the terms can be arranged in two classes of series. Those of the first class contain G terms in A^2, or in B^2, . . . or in N^2, . . . similar to (15), and in each series R has successive values of 0, 1, 2, . . . $(G - 1)$. Those of the second class contain terms in AB, or BC, or . . . MN . . . similar to (16) in which R has the successive values just mentioned.

Let us consider a typical series of the first class. The general term given in (15) can be further expanded to the following form

$$\tfrac{1}{2}KN^2\,\delta\theta\left[\sin 2\pi R/G + \tfrac{1}{2}\sin\left\{(2\nu - 1)2\pi R/G + 2n\right\} - \tfrac{1}{2}\sin\left\{(2\nu + 1)2\pi R/G + 2n\right\}\right]$$

from which it is obvious that the sum of the series in N^2 is zero unless $G = (2\nu \pm 1)$, and that the sum of all the series in this class is zero unless there is at least one component field for which the number of poles is $(G \pm 1)$. Another form of this statement would be: If a component of the field has p poles and $G = (p \pm 1)$ a side-pull will result from this combination, which is obviously true without further explanation.

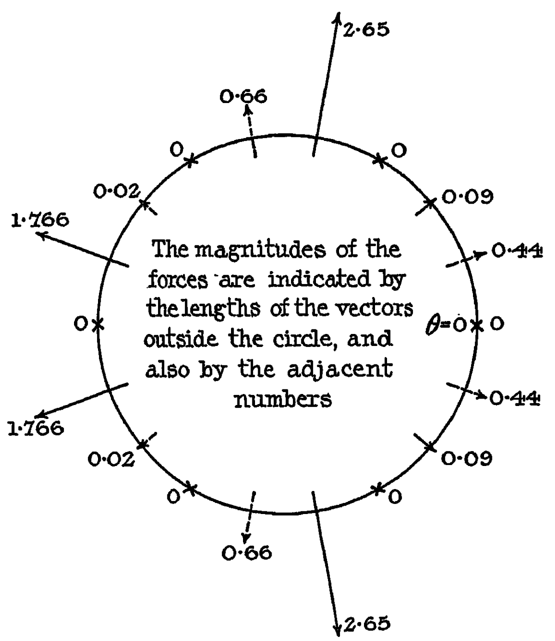


FIG. 10.

Returning now to the series of the second class, the general term (16) can be expanded to the following form

$$\tfrac{1}{2}KMN\,\delta\theta\left[\sin\left\{(\nu - \mu + 1)2\pi R/G + n - m\right\} - \sin\left\{(\nu - \mu - 1)2\pi R/G + n - m\right\} - \sin\left\{(\nu + \mu + 1)2\pi R/G + n + m\right\} + \sin\left\{(\nu + \mu - 1)2\pi R/G + n + m\right\}\right]$$

from which it is clear that the sum of the series in MN is zero unless $G = (\nu \pm \mu \pm 1)$, and the sum of all the series of this class will be zero unless G differs by unity from the sum or difference of the numbers of pairs of poles in any two of the component fields.

The significance of this condition is not very obvious and an example will help to make it clear. Suppose we have a field of four poles ($\mu = 2$) with a fifth multiple of 20 poles ($\nu = 10$), and suppose that $G = 9(= \nu - \mu + 1)$. For the sake of simplicity we will assume that both fields have the same amplitude, so that the flux density at the $(R + 1)$th point will be proportional to

$$\sin 2\pi R/G + \sin 10\pi R/G$$

The full-line vectors in Fig. 10 represent the squares of the nine values of this quantity and clearly indicate the presence of a resultant side-pull. The dotted vectors in the same figure show the values of the same quantities at points midway between the G points already considered; these have been drawn on the assumption that the permeance at the second set of points is one-half that at the first set. The two sets of forces evidently produce a resultant which would not have been present if the permeance had been uniform. If other intermediate sets of points are considered it will be seen that a resultant side-pull must be produced unless the permeance at all points separated by $1/2G$ of the circumference of the rotor is the same.

Returning to the expressions for the cosine terms corresponding to (15) and (16), we find that they can be expanded to

$$\tfrac{1}{2}KN^2\,\delta\theta\left[\cos 2\pi R/G - \tfrac{1}{2}\cos\left\{(2\nu + 1)2\pi R/G + 2n\right\} - \tfrac{1}{2}\cos\left\{(2\nu - 1)2\pi R/G + 2n\right\}\right]$$

and

$$\tfrac{1}{2}KMN\,\delta\theta\left[\cos\left\{(\nu - \mu + 1)2\pi R/G + n - m\right\} + \cos\left\{(\nu - \mu - 1)2\pi R/G + n - m\right\} - \cos\left\{(\nu + \mu + 1)2\pi R/G + n + m\right\} - \cos\left\{(\nu + \mu - 1)2\pi R/G + n + m\right\}\right]$$

Taking first the case of $G = 2\nu + 1$, the components of the resultant force are

$$-\tfrac{1}{4}GKN^2\,\delta\theta \,.\, \sin 2n, \quad \text{and} \quad -\tfrac{1}{4}GKN^2\,\delta\theta \,.\, \cos 2n,$$

respectively.

If the field is moving with respect to the rotor with velocity $+\omega$ we can write

$$n = -\nu\omega t + n'$$

whence we see that the resultant force vector rotates with velocity $-2\nu\omega$ with respect to the rotor. On the other hand, when $G = 2\nu - 1$ the velocity of the resultant force vector is $+2\nu\omega$ with respect to the rotor.

When $G = (\nu - \mu + 1)$ the resultant sine and cosine components are

$$\tfrac{1}{2}GKMN\,\delta\theta \,.\, \sin(n - m) \text{ and } \tfrac{1}{2}GKMN\,\delta\theta \,.\, \cos(n - m).$$

Writing

$$m = -\mu\omega_1 t + m' \quad \text{and} \quad n = -\nu\omega_2 t + n'$$

where ω_1 and ω_2 are measured with respect to the rotor, we see that the speed of the resultant force vector with respect to the rotor is $(\mu\omega_1 - \nu\omega_2)$.

In the same way we find that

when $G = \nu - \mu - 1$ the speed is $-(\mu\omega_1 - \nu\omega_2)$
when $G = \nu + \mu + 1$ the speed is $+(\mu\omega_1 + \nu\omega_2)$

and when $G = \nu + \mu - 1$ the speed is $-(\mu\omega_1 + \nu\omega_2)$.

In all these cases it will be found that the speed of the force vector in space is $Gn_0 - 2f$, where n_0 is the speed of the rotor in revs. per sec., and f is the frequency of supply.

The effect of staggering the rotor slots through one slot-pitch is to make constant the average permeance along any line on the circumference drawn parallel to the axis, and therefore if we consider only the resultant of the radial forces across such a line these resultants will always be in equilibrium, so far as the effects considered under Case (*b*) are concerned, but the radial force is not uniformly distributed along such a line, and if G has one of the values referred to above the forces may be greatest in the middle and least at the ends of one axial line, and least in the middle and greatest at the ends of a diametrically opposite line. Thus there may still be a rotating bending moment acting on the rotor which may conceivably produce appreciable effects on a long rotor.

(10.)

We must now see what rules can be deduced to enable us to choose numbers of slots for squirrel-cage rotors which will avoid these troubles.

(1) *To avoid the effects of interference between fields with numbers of poles differing by two.*—In a three-phase motor the numbers of poles in the component stator fields are p, $5p$, $7p$, $11p$, etc., or, generally $(6d \pm 1)p$, and in a single-phase or two-phase motor they are p, $3p$, $5p$, $7p$, $9p$, etc., or, generally, $(4d \pm 1)p$.

Therefore for a three-phase motor, by Equation (2), we must have

$$(6d_1 \pm 1)p \pm 2 \neq 2Gd + (6d_2 \pm 1)p$$

d_1 and d_2 being positive integers. This reduces to $Gd \neq pd_3 \pm 1$, where d_3 is a positive or negative integer, and since $d = -1$ is the only case of practical importance we finally obtain $G \neq pd_3 \pm 1$, i.e. the number of slots in the rotor must not differ by unity from any multiple of the number of poles for which the stator is wound. For single- and two-phase motors we get the same result. In the case of a four-pole machine, for instance, the rotor must not have an odd number of slots.

(2) In Case (*b*) of Section 9 we have seen that we should not have $G = 2\nu \pm 1$, nor $G = \nu \pm \mu \pm 1$.

For three-phase motors, therefore, we must have

$$G \neq p(6d_1 \pm 1) \pm 1$$

and $$G \neq \tfrac{1}{2}p[(6d_1 \pm 1) \pm (6d_2 \pm 1)] \pm 1$$

Both of these conditions are included in the general condition in Case (1) and the same is true for single- and two-phase motors; thus *if the number of rotor slots is chosen so that it does not differ by unity from any multiple of the number of poles, noise arising from all the causes considered in this paper will be avoided.*

The results of an investigation have been published * recently in which a four-pole, 24-slot stator was tested with several rotors having different numbers of slots. Without exception the rotors with odd numbers of slots were noisy, whilst those with even numbers were quiet.

* W. Stiel: *Zeitschrift des Vereines deutscher Ingenieure*, 1921, vol. 65, p. 147.

(11.)

In order to obtain some experimental confirmation of the foregoing theory the following measurements have been carried out by Mr. W. G. Spencer and Mr. E. I. Sainsbury at Woolwich Polytechnic. The machine employed in the experiments was a 4-h.p. six-pole, 50-period, three-phase motor by a well-known British maker. The squirrel-cage rotor had 41 slots, skewed through one slot-pitch, and the stator had a full-pitch winding in 54 slots. During the starting period this machine ran quite silently at low speeds and also at full speed, but when supplied at normal frequency a definite musical note was emitted between speeds of 600 and 750 r.p.m., and it may be assumed that the speed of the rotating side-pull coincides with the critical speed of the rotor at about the middle of this range. The machine was very rigidly constructed and consequently the note was so faint as to be negligible from a commercial point of view, though it was clear enough for experimental purposes.

For this machine, since $p = 6$, we have $G = 41 = 7p - 1$, a number which should be avoided, according to Section 9.

If we consider the action of the 7th multiple field on this rotor we have $p_3 = 42$, and the possible values of p_4 are

$$p_4 = (2 \times 41 \times d) + 42$$

substituting successively 0, -1, $+1$, -2, $+2$, etc., for d, we obtain the following series of values for p_4 .. 42, -40, $+124$, -122, etc. The 42-pole field produced by the rotor currents combines with the original $7p$-pole field (reducing its value), and this resultant, together with the field for which $p_4 = -40$, produces a rotating side-pull which is the cause of the note observed. The two fields of 122 and 124 poles also produce a rotating side-pull.

Taking f as the frequency of supply and n_0 as the speed of the rotor we have

$$p_3 = p_2 = 42\,; \quad p_4 = p_1 = 40$$

$$n_3 = \frac{2 \times f}{6} \times \frac{1}{7} = \frac{2f}{42}$$

i.e. one-seventh of the speed of the main field, and, since $d = -1$,

$$n_4 = \frac{-82n_0 + n_3 \times 42}{-40} \quad \text{[by Eqn. (9)]}$$

$$= \frac{-82n_0 + 2f}{-40}$$

$$= n_1$$

Since $n_2 = n_3$, the speed of the force vector [by Eqn. (5)] is

$$\tfrac{1}{2}(42n_3 - 40n_1) = 2f - 41n_0$$

We are not concerned with the direction of this rotation,

and in order to deal with a positive quantity we may write for the frequency of the note emitted

$$41n_0 - 2f$$

For the other two fields, with 122 and 124 poles respectively, the speeds must be calculated as for n_4 above.

The speed of the 122-pole field is (d being -2)

$$\frac{-164n_0 + 2f}{-122} = n_1$$

while that of the 124-pole field is (d being $+1$)

$$\frac{82n_0 + 2f}{124} = n_2$$

The speed of the force vector in this case is

$$\tfrac{1}{2}(124n_2 - 122n_1)$$
$$= -41n_0 + 2f, \text{ as before}$$

The pitch of the loudest note emitted by the machine was rather lower than 384 per sec., but for convenience this pitch was taken as standard during the experiments, and a tuning-fork was used as a standard of reference. Power was supplied to the motor at several different frequencies between 0 and 60 periods per sec., and at each frequency the speed was observed at which the note emitted coincided with that of the tuning-fork. The points marked in Fig. 11 show the actual readings obtained, and the line drawn amongst them represents $41n_0 - 2f$. It will be seen that substantial agreement has been obtained. There are two points on the extreme left of the figure for which it does not seem possible to account on the basis of the theory here given.

The faintness of the note emitted by this machine is due to the fact that the slots were skewed, and the effect would have been eliminated entirely if the obliquity had been such that the slot openings extended across two slot-pitches instead of one, though this is scarcely practicable and, in the present case, is quite unnecessary.

Considerable difficulties had to be overcome in order to obtain the results shown in Fig. 11, and the author

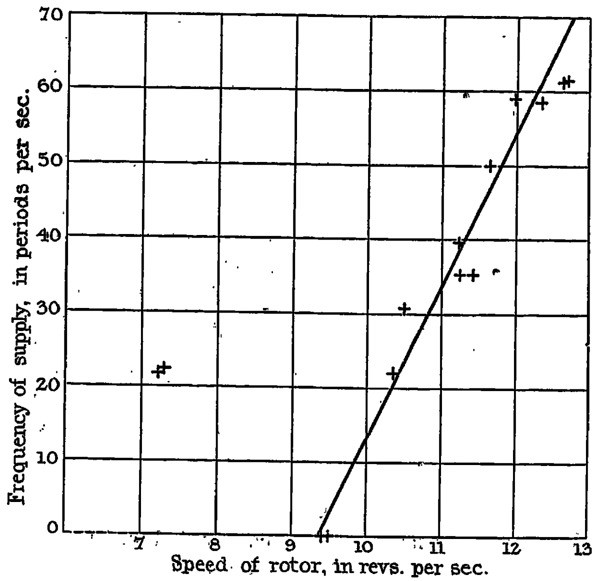


FIG. 11.

wishes to express his indebtedness to Messrs. Spencer and Sainsbury for the care and trouble which they took in making the experiments. It was hoped to show that the critical speed of the rotor was in the neighbourhood of 384 revs. per sec. In this, however, we have not yet been successful, and further experiments are in progress.

AN ELECTRICAL TIMING DEVICE FOR SHORT INTERVALS.

By Professor DAVID ROBERTSON, D.Sc., Member, and NORMAN F. FROME, B.Sc., Student.

(*Paper received* 21*st April*, 1922.)

SUMMARY.

The paper describes a timing device consisting of an inductive resistance in a Wheatstone bridge. The theory of s given and an example of its application.

GENERAL DESCRIPTION.

This arrangement was devised with a view to its application to an industrial purpose, but doubts as to the suitability of delicate relays under works conditions soon caused it to be abandoned for that particular object. As, however, there are uses for it in the laboratory, and it can be easily made up from apparatus which is usually in stock in an electrical laboratory, it is thought that a description may be of interest.

A Wheatstone bridge is made up with three non-inductive arms and one highly inductive arm, as in Fig. 1. When the slider is at C, the point of balance

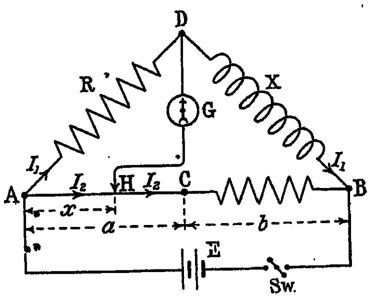


FIG. 1.—Connections of inductive timing device.

for steady conditions, there will be, on switching on the current, a momentary deflection indicating that the slider should be moved to the left. Now place the slider at H, to the left of C. Immediately after switching on, and before the current in the inductive branch has reached an appreciable value, the inductance will absorb practically the whole voltage. Thus D and A will be very nearly at the same potential and the galvanometer current will flow from D to H. Later on, however, the current will flow from H to D. Thus, the galvanometer current will reverse at a particular instant in the growth of the current in the upper arms, and this instant can be varied by adjusting the position of H.

If, instead of the galvanometer, a polarized relay be employed, the first current will deflect the tongue against one stop and the second current against the other. By suitable connections, these movements can be made to close or open an electrical circuit for a definite interval of time, and this secondary circuit may be utilized to control any required operation. By adding other relays, connected to different positions of H, several operations can be obtained in a definite timed sequence.

In the experiments referred to below, R was a 1-ohm coil, AC a 1-ohm slide-wire, while R and X had resistances of 6·44 ohms. X had an inductance of about 1·55 henrys (it is not quite independent of the current used) and thus the time-constant of the R–X circuit was 0·209 second.

The core of the reactor, X, is a rectangle 4 in. × 5 in., with a window 2 in. × 3 in., made from ⊓-shaped Stalloy stampings about 15 mils thick. There are 140 sheets in each packet, giving a gross depth of 2·25 in. and a net depth of about 2·0 in. A press-spahn sheet 11 mils thick was inserted between the two packets at each joint so as to give a definite gap. The effective length of the gap is considerably greater, owing to the unevenness of the edges of the sheets, and to the presence of varnish. The measured inductance corresponds to an effective gap length of 19 mils at each side.

The magnetic path in the iron is 13 in., or say 350 times the effective length of the two gaps. This is somewhat on the high side, but the magnetism left on switching off is still under 5 per cent of the maximum.

The packets of stampings are inserted into two coils joined in series. Each coil has 480 turns in 10 layers, the wire being 20 S.W.G. copper having a diameter of 36 mils bare, and 50 mils over the cotton insulation.

Each gap in the magnetic circuit comes at the centre of a coil. With this arrangement there is little magnetic leakage and the inductance can be calculated with an accuracy practically equal to that with which the gap can be measured.

Current was obtained from a 4-volt storage battery. The current in the reactor would thus be just over ½ ampere, giving a flux density in the iron of about 7 000 C.G.S. units.

Standard Post Office polarized relays were used for the tests, the two 100-ohm coils being in parallel, giving a resistance of 50 ohms. They operated with a minimum current of 2·5 to 5 milliamperes, or 125 to 250 millivolts, according to the adjustment. At first they gave some trouble owing to the vibration of the table when the main switch was put on, but this was eliminated by supporting the relays on felt pads, or on a separate table.

THEORY.

At the initial instant E_L, the electromotive force induced in X, is equal to E, the battery E.M.F., but it decays according to the law

$$E_L = E \times \epsilon^{-T/T_0}, \text{ where } T_0 = L/(R + X)$$

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

For simplicity, we shall assume that the battery resistance and the galvanometer current are negligible, and that we need not take account of the effect of the inductance of the galvanometer branch.

Then, at the instant of the reversal of the galvanometer current, H and D are at the same potential. Consequently,

$$RI_1 = xI_2 \text{ or } I_1 = I_2 \times x/R$$

and $XI_1 + E_L = (a + b - x)I_2$

$$\begin{aligned}
\therefore \quad E_L &= (a + b - x)I_2 - (xX/R)I_2 \\
&= (a + b - x - xX/R)I_2 \\
&= (a + b - x - xb/a)E/(a + b) \\
\therefore \quad E_L/E &= \{a(a + b) - x(a + b)\} \div a(a + b) \\
&= (a - x)/a
\end{aligned}$$

Hence, $\epsilon^{-T/T_0} = (a - x)/a$

or, $(T/T_0) \log \epsilon = \log a/(a - x)$

$$\therefore \quad T = T_0 \times \log a/(a - x) \div \log \epsilon$$

This gives the following values for the ratio T/T_0:—

x/a	0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9	0·95	1·0
T/T_0 ..	0	0·105	0·223	0·357	0·511	0·694	0·917	1·205	1·610	2·303	3·000	∞

CALIBRATION.

Owing to the various disturbing causes mentioned below, the scale cannot be calculated from the constants of the apparatus; it must be calibrated. For this purpose, the duration of the contact in the operated position of the relay was measured by the method

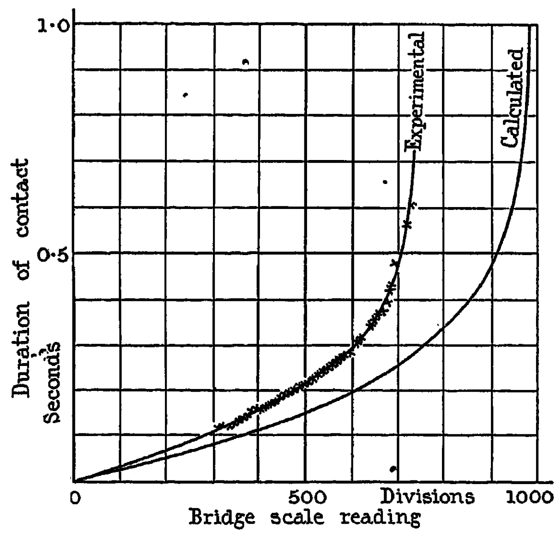


FIG. 2.—Calibration curve of inductive timing device.

of charging a condenser through a high resistance, using the relay as a charge-and-discharge switch with the bias in the discharge position, and the first current sending it to the charge position. A knowledge of the resistance in the charging circuit, and of the capacity of the condenser, enables the duration of the contact to be calculated from the ratio of the ballistic deflection to that obtained on discharging the condenser after it has been completely charged. For

$$Q = Q_0(1 - \epsilon^{-T/T_0}),$$

where T_0 is now equal to CR. Hence,

$$T = T_0 \log Q_0/(Q_0 - Q) \div \log \epsilon$$

In the experiments, R was 200 000 ohms and C 1 microfarad, so that T_0 was 0·2 second.

As will be seen from the graph in Fig. 2, the duration of the contact differs very considerably from the value calculated from the constants of the reactor. There are several causes for this besides the mechanical inertia of the tongue of the relay. Its low voltage-sensibility leads to a considerable delay in its operation, which is enhanced by the effects of the inductance of the relay coils and by the eddy currents in the relay core. Moreover, with the high ratio of iron length to gap length in the core of the reactor, combined with the comparatively high flux density to which it was necessary to run it in order to get reasonable sensibility in the relays, the inductance varied nearly 5 per cent between the maximum value and that with the steady current, while the initial value was about 10 times smaller. Consequently the growth of the current would depart appreciably from the simple exponential law obtained by assuming constant inductance.

Considerable care is required to adjust the relay to the most sensitive setting, and the reading obtained for any given position of the slider varies greatly with this adjustment. On the other hand, with one setting of the relay, the readings can be repeated over and over again with good accuracy so long as the slider is not too near either end of the scale, where the voltage available for operating the relay is too small for certain action. Also, it has been found possible after altering the relay to bring it back again to the former setting by adjusting it to give the same deflection at some one point of the scale; the calibration curve will then be the same as before.

EXAMPLE OF THE USE OF THE DEVICE.

The apparatus was employed for calibrating the scale of an electrical chronometer which was made in the laboratory a number of years ago.* This chronometer was adapted from a Westinghouse type "O" ampere-hour meter by removing the shunt and inserting a series resistance adjusted so that the rotor makes approximately one revolution per second when run on a 4-volt battery. A scale of 100 divisions was marked round the rotor disc to give hundredths of a second, and a scale of seconds on a toothed wheel gearing with the pinion on the rotor spindle.

The instrument has a disc armature with an open-coil winding and a three-part commutator, the windings being enclosed in a double disc of aluminium which also

* D. ROBERTSON: *Journal I.E.E.*, 1915, vol. 53, p. 314.

acts as a brake. Two permanent magnets serve both as motor magnets and as brake magnets.

It was suspected that owing to the action of the commutator there might be sufficient variation of torque in one revolution to make the reading obtained with a short interval of time depend on the initial position of the rotor.

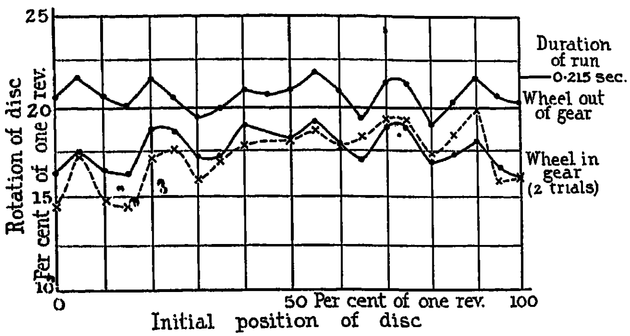


FIG. 3.—Calibration of scale of an electrical chronometer.

The inductive device was therefore connected to start and stop the chronometer the disc of the latter being previously set to some particular position which was varied from time to time. Fig. 3 gives the results and shows unmistakably that the suspected effect does exist, although not to a serious extent. The six peaks on the upper graph, taken with the wheel out of gear, correspond to the six positions in one revolution in which the relative positions of brushes and segments are the same, three occurring at each brush.

The lower graphs, representing two tests with the wheel in gear, show in addition a variation of friction caused by eccentricity of the pinion. Differences between one of these curves and another may similarly be caused by eccentricity or irregularity in the gear wheel, and discrepancies in the same graph may also be due to the same cause if care is not taken to have the same teeth of the wheel in mesh at the separate trials for each point on the curve.

In conclusion, the authors desire to express their thanks to the governors of the Merchant Venturers' Technical College for the facilities for carrying out this work.

THE ENGINEER AND MANUFACTURING COSTS.

By F. C. LAWRENCE, M.C., B.Sc.Tech., Student.

(ABSTRACT *of paper read before the* NORTH-WESTERN STUDENTS' CENTRE, *6th December*, 1921.)

SUMMARY.

The phases of costing discussed in the paper are those which will be of most interest and use to engineers in shops and offices.

An example of the methods of calculating job costs is given, the proportions of the components of the factory costs of various engineering products are illustrated, and the use of mechanical appliances in various calculations is shown to give accuracy and save time in arriving at costs.

The functions of a "work-in-progress" account are described in terms, translated from accountancy to their shop equivalents, showing the actual connection between such an account and the production of a department.

The effect of inaccuracy, which may so easily occur in shop records, is traced through costs to show the delay and unreliability caused thereby; and the necessity of avoiding this inaccuracy is emphasized.

The analysis of the costs of completed jobs gives information which is useful to those engaged in all branches of the industry, and a detailed example of such an analysis is given and described.

As an example of the very many practical services given by a cost department, the relation between the rate of production and the proportion of factory overhead expenses in factory cost is cited.

INTRODUCTION.

In presenting this paper it has been the author's aim to show those aspects of the subject which will enable the engineer to appreciate, first the dependence of costing on his efforts to ensure correct data being sent from the shops and offices to the cost department, and secondly, the value of the facts and figures which, based upon that data, the cost department is able to give to him and to the other members of the factory administrative and executive staffs.

In this abstract it has been thought advisable to delete the introduction to the elements of costing which was embodied in the original paper, and to retain as fully as possible the explanations of the source of the figures as finally presented by the cost department, and their value to those concerned.

Whilst a knowledge of the first principles of costing is, therefore, assumed, it has been found necessary to include a figure showing of what the factory cost is composed and determining the terminology used throughout the paper.

One of the most important factors in satisfactory costing lies in the collection and distribution of the factory overhead expenses to departments and to jobs, a subject which should be of especial interest to engineers.

Only the general method (which is considered by most engineering firms to be best) of distributing the expenses to jobs in the shops, i.e. the machine-hour rate, is indicated in the paper. By the use of this method, for every hour worked on a machine in the shop there is added to the cost of the job an amount equal to the rating of that machine, and by this means the whole of the factory overhead expense should be absorbed by the production of the shops.

Hand labour is classified as a machine group, with its own distinctive rate.

THE GROUPING OF MACHINE TOOLS.

To arrive at machine-hour rates for the distribution of factory overhead expenses, an analysis is made of each item of these expenses so as to divide it amongst the groups of machine tools in a department. From this are determined the total factory overhead expenses attributable to each group. From the records of the machine tools, the working space occupied, the power consumption, the original value and depreciation, the consumption of tools, and any particular expense items, the group into which each one will fall can be determined.

The group number is composed of two figures and is the number noted by the worker on his job ticket. The tens indicate the machine-hour rate and the units the type of machine tool. A practical example is give in Table 1, from which it is seen that Group 24 may contain a number of 5 ft. radial drills rated at 2s. 6d. per hour, while Group 78 covers 10 ft. planers at 9s. per hour.

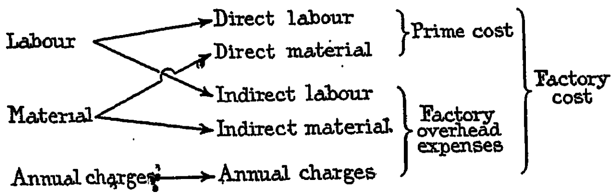
Certain machine tools are not engaged on direct machine labour, and the cost of running and maintaining them is charged to factory overhead expenses, so that they do not themselves carry a machine-hour rate.

AN EXAMPLE OF FACTORY COST.

The manufacture of a large induction motor has been selected as an example and it is proposed to show details in the procedure of arriving at its cost in the section of the cost department, dealing with the costs of the motor assembly department of the factory.

The motor is manufactured on order No. 7106, and during the period of manufacture in the shops, job tickets, in large numbers, will be made out for work done on this order, and each will bear this number. Some will come from the foundry, the forge, the punching department, the coil-winding department and other feeder departments, but such tickets will be dealt with by the feeder department cost sections, for they will receive them with the material requisitions from the motor assembly departments. They will cost the various materials ordered from their departments and deliver to the motor cost section the requisitions on

which the complete cost of their supplies will be given, showing in each case the labour, material and factory overhead expenses, and the total (i.e. factory cost), so that for any transfer in the shop from one depart-



The synthesis of factory cost.

ment to another of finished or part-finished goods, there will be a corresponding transfer in the cost department of a requisition showing the cost.

If in making out the specification of material on any job for the shops, the specification clerk has an extra copy of the specification made which he forwards to the cost clerk concerned, then the latter will at once have before him, in costing the job, the full particulars as to the size, quality, quantity and raw material of each item of the finished machinery or apparatus.

Now, each item is designated on the specification by its drawing number, item number, pattern number and style number, or by whichever of these is desirable. The worker in the shops marks these numbers clearly in the spaces provided on his job ticket, so that it will be seen to be not a very difficult process to connect precisely the job ticket representing any labour in the shops with the materials specified, so that if the original specification sheets are provided with columns for labour, material and factory overhead expenses for the use of the cost department, the cost clerk can collect on these sheets the cost of each specified item, knowing, if he has a requisition or job ticket which does not agree with any item in the specification, either that it has been wrongly entered in the shops or that the specification has been altered, which causes he can at once investigate. If he has shop records showing more than the specified quantities in any item, some previous part has been scrapped or returned for alteration (which scrapping or alteration should have been notified to him by the shops on a suitable form) and again he can trace the omission to its source and discover the true facts.

The cost clerk will receive weekly from the time-keeping department the whole of the week's job tickets for his section, after they have been used to complete the employee's wages. He will receive from the stores the whole of the requisitions, with the costs entered on them from their records, and he will receive from other costing sections the inter-departmental requisitions. His first duty is to sort these under their job number, and he will select the whole of the records booked to this number. From the job tickets he will make a list of the hours worked and the money paid to workers in each machine-hour group, as shown on the left-hand side of Table 2.

The amounts shown on the requisitions will be posted on to the specification against the corresponding items, and the totals of labour, material and overhead expenses will be posted on to the summary sheet of Job No. 7106 against the date.

Each week this procedure will be adopted, from the date when the specifications are received by the cost clerk to a convenient date after he has received the warehouse receipt, which tells him that the motor is

TABLE 1.

Grouping of Machine Tools.

Sub group numbers	Types of machine tools	Factory overhead machine group numbers: 10	20	30	40	50	60	70
1	Centring	Hand labour, and hydraulic presses and bending machines (hand)	—	—	—	—	—	—
2	Vertical boring mills		—	60 in. to 80 in.	Nos. 10 and 8	10 ft. to 12 ft.	16 ft.	—
3	Horizontal boring mills			3¾ in. dia. bar	—	—	—	—
4	Drilling		20 in. vertical, 5 ft. radial, 3 ft. spindle	17 ft. to 19 ft. radial				
5	Surface grinders				—	—	—	—
6	Lathes		20 in. to 42 in. engine	63 in. engine	—	72 in. engine	—	
7	Milling		—	24 in. horizontal slabs	42 in. slab	—	—	—
8	Planing		2 ft. to 3 ft.	4 ft. to 5 ft.	6 ft.	—	7 ft.	10 ft.
9	Miscellaneous		15 in. slotting and shaping, No. 5 keyway cutter	Portable 60 in. planer	—	—	—	—
	Machine-hour rate	1s. 6d.	2s. 6d.	3s.	4s.	5s.	7s. 6d.	9s.

completed and ready for shipment. The convenient date is a few days after the reception of this receipt, thus leaving time for the last few job tickets and requisitions to reach him. He can then arrive at the total figures of labour, material and overhead expenses and the total factory cost of the motor.

TABLE 2.

Abstract of Labour and Factory Overhead Expenses.

Abstract of the Labour and Overhead Costs on Job No. 7106. *Week ending* 10/1/23.

Group No.	Labour		Factory overhead	
	Hours	Wages cost	Rate	Cost
		£ s. d.	s. d.	£ s. d.
10	52½	5 0 7	1 6	3 18 9
20	4	0 9 2	2 6	0 10 0
30	5	0 14 1	3 0	0 15 0
40	—	—	4 0	—
50	3	0 7 5	5 0	0 15 0
60	8	1 0 6	7 6	3 0 0
70	—	—	9 0	—
Totals ..	72½	7 11 9	—	8 18 9

FOUNDRY COSTS.

The description given of costing methods to be used in engineering works has been made as simple as possible. In actual practice the cost accountant is continually meeting problems of no small magnitude.

The costing of the products of a foundry requires very careful handling. Arbitrary values are too often used in distributing the costs, thus leading to wrong results. An iron foundry is naturally divided into at least four parts—the melting, moulding, core-making and dressing sections—each of which calls for different costing methods. The metal at the cupola spout may best be costed at so much per pound, whilst the labour in the other sections may, in some cases, be booked to jobs, and in others to processes. The factory overhead expenses need different treatment in the various sections. The costs of individual castings may all be determined at the end of a month, or predetermined costs may be used throughout the month and an adjustment made at the end of the month. In addition to making castings for the assembly departments, the foundry casts its own equipment. All these and other points need attention, and it is only by a thorough appreciation of them that the true foundry costs can be found.

PERCENTAGE COMPOSITION OF FACTORY COSTS.

In order that the relative importance of the component parts of factory costs may be appreciated, Table 3 has been prepared to show, for a few departments in a typical electrical engineering firm, the percentage composition of its costs.

The question of the standardization of costing methods is here involved. Some firms may include certain material and labour costs as factory overhead expenses, while others may regard them as direct material and direct labour costs; for the border line between prime costs and overhead expenses is not sufficiently distinct to form a universal division.

The figures in the table given must therefore be regarded merely as indicative of the proportions. It will be seen that the assembly departments have, in general, a larger percentage of direct labour and overhead expenses than the feeder departments, because the figures given for them include the labour and overhead expenses transferred from the feeder departments in part-finished goods.

The varying ratio of overhead to direct labour expenses is marked; for the forge it is nearly 176 per cent, while for the coil-manufacturing department it is only 66⅔ per cent.

The annual charges are, on an average, about 10 per cent of the factory overhead expenses.

TABLE 3.

Percentage Composition of Overall Departmental Factory Costs.

Departments	Direct labour	Factory overhead	Material	Labour in factory overhead, i.e. indirect labour	Total labour
Assembly.	per cent	per cent	per cent	per cent	per cent
A—Manufacturing rotary converters, alternators and motors	26	27	47	20	46
B—Manufacturing large electrical transformers ..	19	22	59	12	31
Feeder.					
C—Winding and insulating coils	18	12	70	10	28
D—Manufacturing sheet punchings	13	21	66	12	25
E—Forge	16	27	57	11	27
F—Foundry	35	31	34	22	57

Such figures as the above prove to be very useful in many statistical surveys.

The Use of Calculating Machines.

The processes of costing entail a great amount of sorting of documents and compilation of figures which, if performed by hand, would become not only tedious to the clerks involved but expensive to the firm. For this reason many machines have been called to the service of cost systems, and by their means the speed and accuracy with which cost returns are presented have been greatly increased, while the work of a cost clerk has lost much of its tedium.

The Burroughs adding machine is one of the smaller types arranged for adding sums of money. The Comptometer, another portable machine, does not make a record of the amounts but shows the increasing sum on a series of counters of cyclometer type.

A modified form of the Burroughs machine with duplicate keyboards gives a whole statement of figures at once, while its operation is speeded up by means of an electrical motor drive. This machine is adaptable to the whole preparation of pay-rolls and to other uses in the cost department, while practically the whole of the financial accounts can be prepared on it.

In the processes of summarizing and analysing costs these machines and others of similar function are invaluable as time savers, and in ensuring accuracy of compilation.

At the other end of the scale we have such elaborate machines as the Powers and Hollerith tabulating machines, the latter of which has been very fully described in an article by Mr. E. W. Workman.* These machines should interest the engineer, and particularly the electrical engineer, because of their construction and operation. Their use is restricted to the larger firms, as the expenses of rent (they cannot be purchased) and of maintenance make it necessary that they should be in constant use in order to be economical.

To arrive only at the total cost of orders, the totals of labour and materials costs are needed. To analyse costs, as will be seen later, much detail is required which should not prematurely be called for.

* E. W. Workman: "Cost Accounting by Machinery," *Engineering and Industrial Management*, 1921, vol. 6, p. 314.

Work in Progress.

A most important function of the cost department and one which is of great help to engineers in the shops, is the provision of statements at stated intervals of the work in progress in the shops.

While work is being fashioned in the shops into the products of the factory, it represents portions of the invested capital of the firm. It is obvious that money is made by the turning over of capital, which in turn is effected by the constant progression of work through the shops. It is the duty of the production engineer to arrange the programme of the orders being filled in the shops, and it lies with the cost department to inform him of the value of the work he is thus arranging.

The work in progress is daily absorbing or being charged with new material, labour and factory overhead expenses, and likewise it is being relieved of and receiving credit for the goods it turns out to other departments and the warehouse or shipping department.

Having taken a physical inventory of the value of the total work in progress in a department at the end of a year, the cost department can, each succeeding month, charge the department with its absorption of material, labour and factory overhead expenses, and credit it with its output of finished goods, from the cost records which it possesses; to arrive at the end of each month at a figure showing the new value of work in progress at that date.

Table 4.

Statement of Work in Progress.

(*A*) *Assembly Department. Comparative Statement of Work in Progress,* 1923.

	October £	November £	December £
Charges.			
(1) Work in progress at beginning of month (brought forward)	31 629	28 165	26 622
(2) Direct wages (from the shop pay-roll)	872	913	1 097
(3) Factory overhead absorbed	1 009	1 187	1 310
(4) Goods received from other departments	2 516	2 136	3 373
(5) Direct raw and finished materials	1 275	1 521	2 151
(6) Engineering and draughting salaries, etc.	35	71	142
(7) *Total charges*	£37 336	33 993	34 695
Credits.			
(8) Deliveries to warehouse and other departments	7 702	6 733	7 028
(9) Goods for own uses	547	211	101
(10) Goods shipped direct from outside suppliers	922	427	347
(11) *Total credits*	£9 171	7 371	7 476
(12) Work in progress at end of month carried to next month	28 165	26 622	27 219
(13) Average monthly output for last six months	7 219	6 814	6 371
(14) Equivalent turnover ratio (i.e. no. of months' output in work in progress)	3·9	3·9	4·3

In addition, it can show exactly how the amount of work in progress is distributed over the various orders being filled in the shops, and indicate the rate at which the invested capital is being turned over.

Table 4 gives a typical departmental work-in-progress comparative statement showing each item of the totals* and the monthly variations. Several small items which occur in actual practice have been omitted for the sake of simplicity.

It will be seen that at the end of September there is work in progress to the value of £31 629, and that it has decreased at the end of October to £28 165, i.e. by 11 per cent. A further decrease of 6 per cent is noticed in November, while December shows an increase of just over 2 per cent.

The efforts of the production engineers in reducing the work in progress, i.e. the working capital locked up in the shops, is reflected in this statement. They were successful in October and November but in December, although the deliveries to the warehouse have increased by over 4 per cent, the arrivals of feeder department materials and raw materials to provide for their programme have overbalanced the increase of deliveries and caused the increase in the work in progress.

The turnover is reflected in item 14, which is the quotient of items 12 and 13. While this may not represent the turnover to a great degree of accuracy, it is a very good guide to the speed at which a department is making money for the firm, the speed being inversely proportional to the turnover.

The incorporation of the cost records as cost accounts in the financial books of the firm enables the gross profit made by each department each month to be ascertained.

Reviewing the items shown in Table 4, it can be seen that item 1 is the resultant figure transferred from the previous month. Item 2 is the total paid to the direct-labour workers in the department, taken from the shop pay-roll. Item 3 is the amount of the factory overhead expenses absorbed by this direct labour. Item 4 consists of the cost of part-finished goods (such as rough castings and forgings) received from the feeder and from other assembly departments. The raw materials received and the finished parts purchased from outside suppliers and applied to specific orders appear in item 5, in which also is included those finished parts from outside suppliers which are forwarded direct by them to the customers of the firm and which do not go through the shops (such as oil for bearings or for electrical transformers and steam engines for driving alternators, in cases where they are not made by the firm). Item 6 consists of special charges which are not charged to factory overhead expenses, but are specific to certain orders or jobs.

The total cost of all the apparatus delivered to the warehouse and to other departments is included in item 8, while item 9 contains the cost of all apparatus made for "A" department's own use, and of labour on repairs and renewals in the shop. It is obvious that the difference between items 7 and 11, i.e. the total of the credits, represents the value of the work in progress at the end of the month, as shown in item 12.

* None of the figures used in this paper relate to any particular firm.

Since the whole of the direct wages, factory overhead expenses and materials have been used on specific orders, the total of the costs added to these orders during the month will agree with the totals of items 2, 3, 4 and 5. The work for the department itself is done on an internal order and costed in precisely the same manner as customer's orders, and the totals of the costs to date of all orders that have not been closed will agree with the work-in-progress balance, so that should the production engineer query the magnitude of this balance, he can be told at once exactly of what it consists.

The Shop Staff in Relation to Shop Records.

If the cost records are to be accurate and reliable, the shop records, which form practically the whole data from which they are built, must be accurate and complete in every detail. In other words, in order that the cost department may give the engineers and the management reliable costs and cost figures, the engineers in the shops must first give to the cost department documents which unerringly represent what actually has taken place in the shops.

Now it is almost impossible for an employee to draw from the stores the direct material which he requires for his jobs without giving requisitions agreeing in detail with the material he receives, as specified for each job.

The direct labour is in most cases accurately accounted for, but even in this case loopholes occur for wrong booking (for example, where the employee spends a short time on each of many small jobs he is liable to book his time spent on several jobs to one only, in order to save himself the trouble of writing out several tickets).

The indirect labour and indirect material bookings are the source of many troubles, and the factory overhead expenses of which they form by far the largest proportion is no small part of the total factory cost, as will have been noted from Table 3. In the first place a foreman will strive to cut down his factory overhead expenses; secondly, the employee will have constantly to refer to a list of overhead items in order to book correctly; and thirdly, unless detailed explanation is given as to what is to be and what is not to be booked to each item of overhead expenses, indecision will lead to a proportion of wrong bookings.

While the cost department will lend its aid in planning the means of booking all the items, the department looks to the engineer in the shops to see that these bookings are correctly made.

If many incorrect bookings are made in the shops it must necessarily take much time on the part of the cost department to have the corrections made, thereby occasioning delay in the presenting of costs, undermining the exactitude of the results, and greatly increasing the expense of running the cost department, with a resultant increase in the cost of each piece of apparatus turned out from the shops.

Dislocation of work, consequent delay and increased expense may also be occasioned by the late receipt of job tickets and requisitions from the shops and stores. In this direction the engineers concerned may help, at

TABLE 5.

Analysis of Factory Cost, Motor Assembly Department.

Factory Cost of One Induction Motor, Type SR, Frame 4331, 575 H.P., Three-phase, 50 Periods, 500 Volts, 480 R.P.M., for A.B. Company, Limited. Order No. 7106.

Column	1	2	3	4	5	6	7	8	9	10	11	12	13
Parts	Section No.	Quantity	Name of part	Weight	Mach. group no.	Direct hours: Groups	Direct hours: Parts	Labour cost: Groups	Labour cost: Parts	Overhead cost: Groups	Overhead cost: Parts	Material costs	Total factory costs
				lb.				£ s.	£ s.	£ s.	£ s.	£ s.	£ s. d.
Mech'l parts of stator	1	1	Cast-iron yoke ..	2 800	10	60	—	4 10	—	4 10	—	—	—
					30	25	—	2 5	—	3 15	—	—	—
					50	35	—	3 10	—	8 15	—	—	—
					70	5	—	0 10	—	2 5	—	—	—
					All	—	125	—	10 15	—	19 5	96 10	126 10 0
	2	—	Magnetic circuits ..	2 000	—	—	—	—	—	—	—	201 2	201 2 0
	3	—	Assembling circuits ..	—	10	125	125	—	10 14	—	9 7½	4 1	24 2 6
	4	2	W.I. end plates ..	—	30	15	15	—	0 15	—	2 5	16 15	19 15 0
	5	2	End brackets	2 400	10	180	—	16 1	—	13 10	—	—	—
					20	20	—	1 14	—	2 10	—	—	—
					30	45	—	4 11	—	6 15	—	—	—
					50	35	—	3 12	—	8 15	—	—	—
					60	30	—	4 3	—	11 5	—	—	—
					All	—	310	—	30 1	—	42 15	137 16	210 12 0
Mech'l parts of rotor	6	1	Cast-iron spider ..	1 600	10	10	—	0 13	—	0 15	—	—	—
					20	35	—	3 7	—	4 7½	—	—	—
					All	—	45	—	4 0	—	5 2½	81 2	90 4 6
	7	—	Magnetic circuits ..	1 700	—	—	—	—	—	—	—	168 7	168 7 0
	8	—	Assembling circuits ..	—	10	135	135	—	13 6	—	10 2½	2 1	25 9 6
	9	2	End plates	350	30	20	20	—	2 1	—	3 0	33 3	38 4 0
	10	1	Shaft	800	20	55	—	5 7	—	6 17½	—	—	—
					30	5	—	0 12	—	0 15	—	—	—
					All	—	60	—	5 19	—	7 12½	53 1	66 12 6
Elec'l parts of stator	11	—	Coils and connections	700	—	—	—	—	—	—	—	297 10	297 10 0
	12	—	Winding and assembling	—	10	475	475	—	21 2	—	35 12½	—	56 14 6
	13	—	Brush-gear	—	10	10	10	—	1 1	—	0 15	37 16	39 12 0
	14	—	Terminals, etc... ..	—	10	25	25	—	1 17	—	1 17½	19 8	23 2 6
	15	—	Trifurcating box ..	—	—	—	—	—	—	—	—	17 1	17 1 0
Elec'l parts of rotor	16	—	Coils and connections	600	—	—	—	—	—	—	—	416 1	416 1 0
	17	—	Winding and assembling	—	10	425	425	—	23 7	—	31 17½	65 5	120 9 6
	18	—	Slip-rings, etc.	—	10	5	5	—	0 11	—	0 7½	16 18	17 16 6
	19	2	Pillow blocks	750	10	85	—	7 7	—	6 7½	—	—	—
					20	45	—	3 11	—	5 12½	—	—	—
					30	60	—	5 19	—	9 0	—	—	—
					All	—	190	—	16 17	—	21 0	27 2	64 19 0
Other parts	20	2	Bearings	—	10	40	40	—	3 1	—	3 0	23 2	29 3 0
	21	—	Assembly	—	10	155	155	—	14 6	—	11 12½	—	25 18 6
	22	—	Testing	—	10	90	90	—	7 2	—	6 15	—	13 17 0
	23	—	Finishing	—	10	5	—	0 12	—	0 7½	—	—	—
					20	25	—	2 18	—	3 2½	—	—	—
					40	5	—	0 8	—	1 0	—	—	—
					All	—	35	—	3 18	—	4 10	7 6	15 14 0
			Totals	—	—	—	2 285	—	170 13	—	216 17½	1 721 7	2 108 17 6

SUMMARIES.

Group Hours.

Group	Hours	Direct labour	Factory overhead
		£ s. d.	£ s. d.
10	1 825	125 10 0	136 17 6
20	180	16 17 0	22 10 0
30	170	16 3 0	25 10 0
40	5	0 8 0	1 0 0
50	70	7 2 0	17 10 0
60	30	4 3 0	11 5 0
70	5	0 10 0	2 5 0
Totals	2 285	170 13 0	216 17 6

Factory Costs.

	From above	Approximate analysis of material	Final analysis
	£ s. d.	£	£
Direct labour ..	170 13 0	313	484
Factory overhead cost	216 17 6	332	549
Material	1 721 7 0	1 076	1 076
Totals	2 108 17 6	1 721	2 109

least, to speed up the information which they themselves require.

Analysis of Costs.

The most important functions of the cost department are, first, to ascertain the costs of production, and, secondly, to analyse those costs. The purpose of analysing a cost is to demonstrate exactly where each item of the factory cost has been incurred, in order that it may be known where costs can be cut down, and also to provide the selling departments with data upon which to base their prices to customers who make inquiries. The designer must know the cost of the machines or apparatus which he designs, and the estimator must know the costs of previous machines or apparatus built, in order to have bases on which to make new estimates for the selling department. The management must have costs to enable them to determine what lines of machines are profitable to construct, and each of them requires the analysed costs.

Table 5 shows the cost analysis of job No. 7106, the method of compiling the costs of which was shown earlier in the paper. Only a very brief survey of the main points of this analysis is possible here.

The amount of detail shown is dependent on the amount called for, as it will be appreciated that many sub-divisions of material, labour and factory overhead costs could be given.

In this case the motor has been assembled in the motor assembly department, and the direct labour and factory overhead costs are those incurred only in this department. Thus the material figures contain, in addition to all the direct material, the labour and factory overhead costs transferred to the job from other departments.

The direct labour cost is detailed for each part as shown in Table 2.

Group 10 represents hand labour, 60 hours of which on the yoke cost £4 10s.

In group 30, 25 hours' work on the smaller machine tools costs £2 5s., while 5 hours' work on large machine tools (such as a 10-ft. planer) costs 10s.

On the yoke the labour represented by this amount would have been used in rough machining, drilling, lathe work, slotting and planing, in addition to the hand labour in filing, chipping, etc.

Cols. 7 and 9 show merely the sum of the hours worked and the money spent on each section. The factory overhead is applied as shown in Table 3. Col. 10 shows the factory overhead applied to groups, and col. 11 the total factory overhead cost for each section.

The material costs occupy col. 12, and include direct raw material drawn from the motor assembly department's stores, feeder material (including the labour and factory overhead applied to it in the feeder departments), stock parts (including labour and factory overhead), and finished parts from outside suppliers.

The totals of cols. 9, 11 and 12 are carried in one figure into col. 13, which then shows the factory cost of each section.

By applying the percentages given in Table 3 it is deduced that the total material consists, as far as this work is concerned, of

		£
Direct material	.. ..	1 076
Feeder department and stock parts	Direct labour	813
	Factory overhead ..	332
		£1 721

so that the eventual analysis of the factory cost is shown to be

Direct labour	484 =	(23 per cent)
Factory overhead	549 =	(26 per cent)
Direct material	1 076 =	(51 per cent)
	£2 109	(100 per cent)

In addition to what has been given in this analysis, there might be shown the division of labour into day-work and piece-work (in hours and money), analysed to operations, with the factory overhead cost correspondingly divided. The "material" in col. 12 might have been split up into feeder department and other labour and factory overhead expenses, or the motor might have been further sectionalized. All of this it is possible to obtain from the data in the hands of the cost department. The example shown has been purposely kept as simple as possible, but it is sufficiently detailed to show the value of a complete cost analysis to certain of the engineering staff of a factory.

Effect of Increased Production on Factory Overhead Expenses.

With all the data which it possesses the cost department is able to be of further service to the engineering staff. For instance, if a large demand is assured for a particular line of machines the engineers may plan a system of standardized manufacture. This should lead to increased production which, in its turn, will affect the factory overhead expenses, for, with an increase in production in any one department, while the productive labour cost will increase more or less proportionately, the factory overhead expenses will increase at a lower rate.

The overhead machine-hour rates may therefore be reduced in anticipation, which means that any one job will bear a smaller proportion of the factory overhead expenses than it did previously, and thus the factory cost will be correspondingly reduced.

Conclusion.

The choice of a few of the many activities of a costing department which those entering upon a career in engineering should know of and appreciate, means the omission of many others which would claim the engineer's attention. It is hoped that the brief descriptions of methods and aims embodied in this paper will stimulate the necessary interest of engineers and go some way to ensure their co-operation with the cost department, the ultimate success of which is so dependent on their aid and appreciation.

THE TESTING OF MATERIALS USED IN THE MANUFACTURE OF ELECTRICAL EQUIPMENT.

By C. Dawson, Student.

(Abstract of paper read before the South Midland Students' Section, 15th November, 1921.)

Summary.

The following tests are described:—

Metals.—Tensile, compression, shearing, bending, torsion, impact, hardness, magnetic (rods and core plates), and miscellaneous.

Insulating Materials.

(*a*) *Sheet and moulded insulation.*—Mechanical strength, plastic yield, electric strength, and insulation resistance.

(*b*) *Oils.*—Electric strength, insulation resistance, viscosity, flash point, chemical reaction, and sludge.

(*c*) *Varnishes.*—Electric strength, flexibility, acidity, and time of drying.

The procedure on delivery of material is also set out.

Introduction.

The practice of testing all deliveries of raw materials has greatly developed during the past few years, and every large manufacturer has now a fully equipped testing department, the object of which is to detect faulty material before it passes into the shops. Otherwise a considerable amount of time and labour may be wasted. It is also an invaluable guide to the buying department.

Generally, for any given material, several sources of supply are available, and it is important to be able to distinguish the quality of the materials coming from different sources, as they may differ considerably in grade or cost, and no mere supervision of the process of manufacture, or external examination, is an adequate guarantee of quality. To ensure that the supplier understands exactly what is required of him a specification is circulated. This is merely a statement of what is, or is not, wanted and the tests which the materials will have to pass. A knowledge of any one of the following points is generally required:

(1) Is the material suitable for the purpose?
(2) Is the material good of its kind?
(3) Is the material as good as that in previous deliveries?
(4) Of two materials, equally available, which is the better?

The simplest way of determining these questions is to select samples of the material and subject them to appropriate tests, and, since a rapid and definite judgment is required, more or less arbitrary standards of quality must be accepted. Since the physical constants of a material really determine its value for constructive purposes, commercial tests may be made to approximate as closely as is practicable to tests for scientific purposes. Whenever possible, shorter and readier methods are applied.

Metals.

Of the mechanical properties, engineers are concerned with the strength, toughness, hardness or adaptability of the metals to the mechanical operations of the workshop. To characterize these mechanical properties simple tests, such as tensile and bending tests, etc., are adopted and they suffice, except in one or two extreme cases, to detect faulty or unsafe material.

Tensile test.—The simplest method of performing a tensile test is to fix one end of the sample and attach weights to the other end. This is quite satisfactory where the sectional area of the sample is small, as in the case of wire, but for larger samples levers are employed so that a large load may be obtained with a small weight. Machines testing up to about 100 tons are made with a single lever and are generally used. Larger multilever machines are made, but are beyond the needs of the electrical manufacturer.

The sample should represent the average quality of the delivery, i.e. neither the best nor the worst should be chosen, but a piece which is representative of the whole. To prevent confusion the bulk and the sample should both be branded before detaching the latter. It is important that it should not be subjected to any harsh treatment such as bending, hammering or heating, as this would probably alter the properties of the sample. All samples should be of similar shape, as this may have a great influence on the results obtained. The British Standard Specifications give standard forms of test-pieces, and all these, except test-piece F, give approximately the same results. It will be noted that the gauge length is less than the parallel length. This is because with ductile materials, such as mild steel, some of the metal from the enlarged ends flows into the adjoining part of the reduced section, thus decreasing the elongation and contraction, and increasing the strength of these parts. All changes of section must be gradual to avoid uneven stressing at these points. According to the B.E.S.A. specification, if one sample does not reach the specification standard, two others should be taken and if either of these fails the delivery may be rejected.

The elongation is a measure of the permanent set and is a good criterion of the ductility of the material. For a given gauge length the elongation increases with increased diameter, so that the necessity of specifying the proportions of the test-piece is evident. Another

guide to the ductility is the reduction of area, expressed as a percentage of the original area.

In the opinion of some engineers the reduction of area is a better indication of the ductility than percentage elongation, but it cannot be measured so accurately. It is also much affected by local defects and the two are in agreement only when the elongation is measured for a very short length of test-piece near the fracture. Other tests for ductility will be dealt with later.

Examination of the fracture.—The fracture should always be examined, as the appearance of the fractured surface is generally an index of the character of the material. The metal is said to be "crystalline" when made up of visible crystals either coarse or fine. When the crystals are too fine to be recognized as such the metal is said to be "granular," and, when very minute, "silky." Wrought iron gives a "fibrous" fracture. Cast iron is sometimes broadly classed as white or grey, according to whether the fracture is light or dark. The latter contains a higher percentage of graphitic carbon than the former. Generally, a coarsely crystalline or granular metal has less satisfactory working properties than one of the same class in which the fracture is finer. The size of grain often depends largely on the temperature at which the metal was cast, and upon the subsequent thermal and mechanical treatment and rate of loading.

The fracture of ductile materials under tension, and of brittle materials under compression, generally takes place partially or wholly by shearing, or sliding, in directions oblique to that of the direct stress. For tensile tests the shape of fracture of mild steel is a truncated cone, and it is interesting to note that the angle of the cone is always approximately 45°. In the case of cast iron, however, there is no cone, but practically a plane surface.

Cast iron is often tested in the form of beams 36 in. × 2 in. × 1 in. supported at the ends and loaded in the centre. It should not break when a load of 28 cwts. is applied, and the maximum deflection should be not less than 0·33 in. If from these results the tensile strength is calculated, the resulting figures, called the "modulus of rupture," will be higher than those obtained for the tensile test.

Compression test.—A table may be suspended from the shackle, below the cross-head of the testing machine, so that the sample can be crushed between the cross-head and the platform. To prevent bending, the length of the sample should not exceed two or three times the diameter. The sample is placed between hardened steel plates, and to ensure axial loading one plate is fitted with a ball joint. Hard or brittle materials generally fracture under compression by shearing across some plane oblique to the direct compressive stress. Plastic materials shorten almost without limit, expanding at the same time, and so require higher loads to effect further compressive strain. An ultimate strength is therefore difficult to specify.

Shearing test.—This can be carried out in a similar way to the compression test by placing the sample in a suitable holder.

Bending test.—The machine is set up as for a compression test, except that a plunger is fixed to the cross-head. The plunger applies the load to the centre of the sample which is supported near each end on rounded edges. By this means the sample is bent to approximately a right-angle. The load is taken off, the plunger is removed, and the sample is now placed on end and the load re-applied, and the bending continued. When a machine is not available the sample may be bent by hammering. The bending test is a rough guide as to the ductility of the material. When testing flat samples the sides should be planed, as if they are merely sheared the test is more severe and less trustworthy. The sample should, without cracking, be capable of being bent round a radius of 1½ times the thickness of the sample until the sides are parallel. Sometimes bending tests are made while hot to detect "red shortness," i.e. brittleness when hot. Another rough, workshop test for ductility is the drifting test, in which a hole is drilled near an edge of the plate and then drifted out to a larger size.

Torsion test.—When a bar is fixed at one end and a couple applied at the other in a plane perpendicular to the axis of the bar, it suffers a deformation (termed torsion) which gives rise to simple shearing stresses. Tensile and compression tests give no indication as to the torsion-resisting properties of the material, and materials for shafts, etc., should therefore be subjected to a torsion test. With a special attachment this can be carried out in the tensile-testing machine previously described. The fracture of a ductile material under torsion is practically in one plane at right-angles to the axis. On the other hand, the fracture of a brittle material forms a helix of one turn returning parallel with the axis until it reaches the starting point.

Impact test.—Occasionally a material which satisfies the above tests will fail when subjected to shock or vibration, and it is sometimes advisable to apply an impact test. Such materials are sometimes called "fragile," as they break with little deformation and a small expenditure of mechanical work. For this reason the work done in fracturing the material is measured. An impact test is not usual in electrical work, except for some insulating materials.

Fatigue test.—Materials subjected to varying stresses sometimes become fatigued and fail. Special tests for this property are not usual for electrical work, as the tensile strength is also an index of the resistance to fatigue.

Hardness test.—There is no absolute measure of hardness and therefore comparative methods are used. The earliest method was to take various substances to find which would scratch the material under test. A modification of this is the sclerometer in which a diamond or steel point is weighted, and the weight required to produce a scratch is noted. This is more suited to brittle than to ductile materials. Another method, suited to ductile materials, is an indentation test such as the Brinell test. In this test a hardened steel ball (10 mm diameter) is forced into the material tested, generally at a polished face, by static pressure. The diameter of the impression is observed by means of a microscope, and the hardness is read off from a table which takes into account the relation between the diameter and the depth, which is the real measure

in this case. For the ferrous alloys a pressure of 3 000 kg is used, and for the copper alloys 500 kg. The pressure may be applied by a dead weight, by levers, or by fluid pressure. In the Shore scleroscope a weighted conical diamond falls through a given height and the height of the rebound is noted. Different hammers are used for ferrous and copper alloys. This method is suited to finished articles as it avoids disfigurement, but the results are often influenced by the method of supporting the sample. For malleable iron it is advisable to test the sample by sawing or machining, because if not properly annealed it is liable to be harder in the centre. It should not be harder than 200 Brinell.

Chemical test.—The material should be machined and the drillings carefully kept and placed in a bottle, which should then be labelled and sent to the chemist for analysis. The actual work of the chemist is of little interest to the engineer but from the results obtained much may be learnt, and it is important to know the effect of the various constituents as these indicate the properties of the material.

Photo-micrographs.—These are taken only in the case of faulty material or perhaps such important parts as rotor forgings and retaining rings. The microscope shows, amongst other things, the nature of any impurities, and the previous mechanical and heat treatments.

Inspection.—The dimensions of all materials bought to size are checked, e.g. bars and rods, wire, slate and boiler plate for switch cubicles.

Magnetic tests.—This branch of the subject is of growing importance because, apart from the necessity of testing for purely magnetic purposes, much work has been done of late years in connection with the correlation of the magnetic and mechanical properties. The characteristics which are of importance to the engineer are permeability, residual magnetism, coercive force. hysteresis and eddy-current losses.

The following are some of the methods of measuring permeability.

(1) *Tractional method.*—The force necessary to separate two parts of a magnetic circuit is measured as in the Thompson permeameter and Ewing's magnetic balance. These give approximate relative values. The Du Bois magnetic balance is also of this type and is more sensitive than the other examples given.

(2) *By a steady magnetic or electric action* as in Koepsal's permeameter. In principle the device is similar to a millivoltmeter in which the permanent magnet is replaced by an electromagnet, the sample under test forming part of this electromagnet. The moving coil of the instrument, carrying a small current supplied by a dry cell, takes up a position determined by the main flux. This instrument is very sensitive but is affected by stray fields. The Esterline permeameter and Ewing's permeability bridge are other examples of this method.

(3) *By measuring the increase in the electrical resistance* of bismuth when placed in a magnetic field.

(4) *By an inductive discharge through a ballistic galvanometer.*—There are several permeameters of this type, but that recommended by C. V. Burrows of the Bureau of Standards, Washington, is probably the best.*

* See *Scientific Papers of the Bureau of Standards*, No. 117.

Hysteresis and eddy-current losses.—In the case of core plates the losses are readily determined by means of a special transformer known as the Epstein square. The iron core is easily replaced and is formed by the iron under test. About 4·5 lb. of the iron is cut with sharp shears into strips 10 in. × 2 in., half being parallel to, and half at right-angles to, the direction of rolling. These are made up into four equal bundles, two from each direction of rolling, with press-spahn between each strip, and assembled in the apparatus. At the corners the magnetic circuit is completed with short pieces of the same or similar material bent at right-angles and interleaved between strips of adjacent bundles. A clamp is tightened over these laps to give a good magnetic joint. There are two secondaries wound under the primary, one of which is connected to a voltmeter for determining the flux (generally 10 000 lines per sq. cm). Unless an electrostatic instrument is used, a correction should be made for the current taken by the voltmeter. The other secondary is connected to the voltage coil of a low-reading wattmeter, the current coil of which is in series with the primary of the transformer. By this means the copper losses in the transformer are eliminated. For accurate work a correction may be made for the copper losses of the wattmeter potential coil. The sine-wave voltage applied to the primary is adjusted by an auto-transformer, not a resistance, until the flux is correct as indicated by the voltmeter, and then the wattmeter is read. Whenever the magnetizing circuit has been broken it should be closed through a considerable resistance, which is then gradually cut out. This prevents a large first surge and consequent high magnetization which would require subsequent demagnetization. As the hysteresis losses vary as the frequency, and the eddy-current losses vary as the square of the frequency, by repeating the experiment at another frequency the two losses may be separated.

Conductivity.—Copper and resistance wires should be checked for resistance.

Insulating Materials.

Sheet and moulded insulators.—The most important properties of this class of material are mechanical strength, plastic yield with temperature, electric strength, insulation resistance and absence of metallic inclusions. A convenient method for comparing the strength of these materials is in the form of a cantilever, the effective length of which is 150 mm, the breadth 15 mm and the depth 15 mm. When samples are received in another form they are best compared with a standard product of the same size. Then, if the results of previous tests applied to the standard product are known, the material can be compared with any other. The plastic yield with temperature can be determined by loading the cantilever with a 2-lb. weight, placing it in an oven at 75° C. for 2 hours, and noting the deflection produced with the weight removed. The temperature must be very carefully watched.

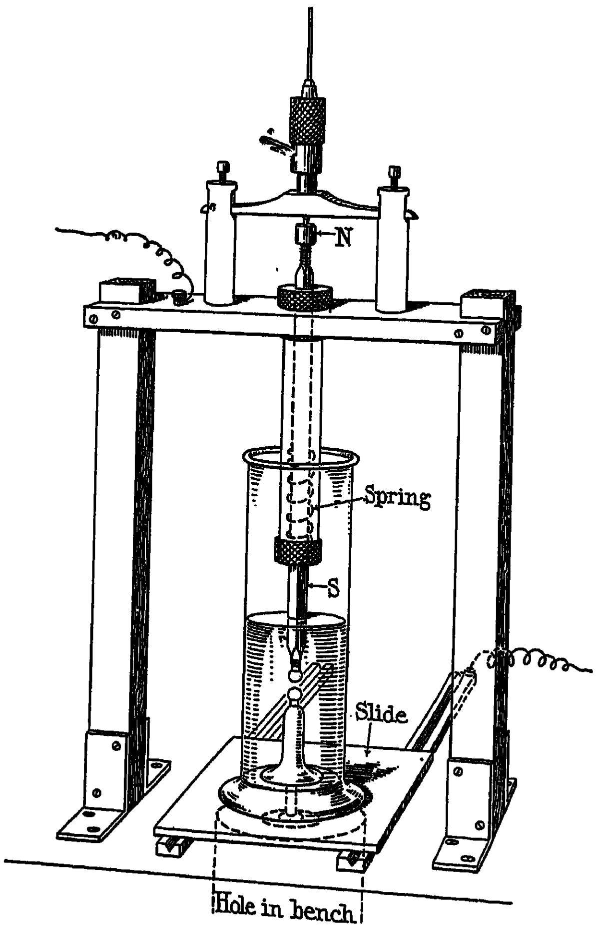
Impact.—The number of times which the sample may be dropped from a given height on to a concrete floor without breaking is noted, or a small Izod testing machine may be used.

Electric strength.—Samples, the thickness of which is

known, are placed between electrodes under a pressure of 3·5 lb. per sq. in. The secondary of an extra-high-tension transformer is connected to the electrodes and the voltage raised by varying the primary voltage by means of an auto-transformer until breakdown occurs. Some materials, e.g. ebonite, are tested under oil.

Insulation resistance.—This is determined by means of a high-voltage "Megger." If this is not sufficiently sensitive a high-voltage battery with a galvanometer and a limiting resistance in series is used.

Metallic inclusions.—For some materials, such as



Apparatus for testing the electric strength of oil.

press-spahn for high-tension work, every sheet is submitted to X-rays to detect metallic inclusions.

Oils.

Switch and transformer oils are obtained from crude petroleum by fractional distillation. A sample should be drawn from each barrel of oil and tested for electric strength, insulation resistance, viscosity, flash point, chemical reaction and sludge.

(*a*) *Electric strength.*—One method of testing this is shown in the figure on this page. The oil is drawn from the barrels by means of a pump or syringe kept for the purpose, and put in the glass jar, which is first rinsed with some of the oil—on no account must water be used. The bottom of the jar is drilled and a brass stud fitted. The lower electrode should be so heavy as not to be lifted by the electrostatic attraction. The jar is now placed in position by means of the sliding base. The micrometer is set at zero and the length of the spindle S adjusted by turning the nut N at the top of the spindle until the two electrodes just make contact. This is determined by means of a bell and battery. The micrometer is now turned until the required spark-gap is obtained. The bell is disconnected and the extra-high-tension leads connected up, the voltage being varied by means of an auto-transformer or induction regulator.

With spherical electrodes 0·25 in. diameter separated by 0·07 in., the oil should withstand 9 000 volts without sparking. It is very difficult to obtain consistent results when carrying out this test, and it is advisable to let the oil stand for some time after setting up the apparatus, to allow the fibres in suspension to settle. Larger electrodes with a wider gap will probably overcome this difficulty. The electric strength is greatly affected by the smallest trace of moisture and may be taken as a guide to the amount of moisture present. Another way to detect the presence of moisture is to thrust a red-hot wire into the oil. If moisture is present a crackling noise is heard, and if the oil is dry there will simply be a puff of smoke. The best method is to drop in a small piece of sodium, which decomposes any water present and liberates hydrogen.

(*b*) *Insulation resistance.*—Some engineers maintain that insulation resistance is a better criterion of the quality of the oil than the electric strength, but the difficulty is that the insulation resistance changes with temperature. The oil is placed in a jar, and disc electrodes of almost the same diameter as the internal diameter of the jar are separated by a definite amount and connected to a "Megger."

(*c*) *Viscosity.*—There are several methods of determining the viscosity, but the Redwood viscosimeter is probably the best for electrical work. The viscosity of transformer oil should not be above 850 seconds Redwood at 40° F. or it will not carry away the heat with sufficient rapidity. For oil switches the oil should not be too thin; at, say, 70° F. the viscosity should not be less than 100 seconds Redwood, otherwise the arc will not be extinguished.

(*d*) *Flash point.*—This is the lowest temperature at which the oil gives off inflammable vapour. This should not be below 150° C. when tested in a closed testing apparatus such as Gray's.

(*e*) *Chemical reaction.*—The presence of an acid or alkali in the oil reduces the electric strength, and an alkali also gives the oil the power of absorbing moisture. To test for these impurities the oil is shaken with an equal volume of boiling water in a separator and kept at nearly 100° C. until the separation is complete, when the aqueous solution is tested. The presence of any acid or alkali is shown by adding phenolphthalein. Tincture of cochineal prepared with 20 per cent of alcohol is sometimes used, but it is too sensitive. It turns yellow if an acid is present, violet-blue if alkaline, and red if neutral. Resin is also shown in this test by its precipitation in fine white granules at the point

of separation of oil from water. The presence of sulphuric acid and sulphonates can be detected by a white precipitate forming when barium chloride solution is added. The presence of sulphur is detected by immersing copper wire in the oil and noting whether the copper blackens. Mineral impurities and additions may be tested by evaporating and igniting the oil and testing the residue.

(*f*) *Sludge*.—Sludge consists of oxidation products of the oil, which collect in and around the windings of oil-immersed transformers and choke the cooling ducts. In the case of oil switches it is not of much importance, as the growth is slow and the parts are easily accessible for cleaning. One test for sludge is to draw pure air through 100 cm³ of oil heated to 150° C. in a 200 cm³ flask, fitted with a condenser neck, at the rate of 3 bubbles per second (0·07 cubic ft. per hour). The deposit formed can be weighed by diluting the oil with petroleum spirit, and filtering and washing with more petroleum spirit. The deposit should not weigh more than 0·05 per cent of the original weight. A piece of bright copper having a total surface of 4·5 sq. in. must be placed in the flask during the test, as this has a catalytic action. The disadvantage with this method is the time required, viz. two days.

Varnishes.

Insulating varnishes are tested for :—

(1) *Dielectric strength*.—A layer of No. 18 S.W.G. double-cotton covered wire is wound round a brass rod; then warmed and dipped in the varnish. When dry the electric strength between the wire and the rod is determined; this will be about 800 volts a.c. A better test is to use the impregnated paper employed in the flexibility test, for which 600 volts per mil is a fair figure.

(2) *Flexibility*.—Strips of thin paper are impregnated with several coats of varnish and stoved for several days till the paper cracks on bending it about 50 times round a radius of 0·006 in. A good varnish will withstand heating for 14 days at 130° C.

(3) *Acidity*.—Lengths of copper wire are immersed and stoved. If any acid is present the copper turns green. Another test is to add plenty of alcohol, shake and titrate with potassium hydroxide.

(4) *Time of drying*.—The time of drying the above-mentioned strips of paper is noted. Insulating varnishes stoved at 85° C. should dry overnight. Air-drying finishing varnishes dry in from 2 to 10 hours.

(5) *The effect of the varnish on the enamel* when for use with enamelled wire.

TABLE 1.

Tests usually applied to the Various Materials, and Average Figures obtained.

Material	Tensile strength	Bend	Hardness (Brinell)	Permeability ($H = 100$)	Hysteresis and eddy currents	Miscellaneous
	tons/sq. in.	degrees			watts/lb.	
Rotor forgings	35–45	180	170	180	—	Chemical analysis
Rotor retaining rings	50–56	180	250	—	—	Chemical analysis
Steel rod	33–47	180	140–200	—	—	Chemical analysis
Malleable iron castings	—	—	130–190	—	—	Machining
Pig iron	—	—	—	—	—	Chemical analysis and drop test
Cast iron	12–16	—	—	80–90	—	Chemical analysis
Core plates	—	—	—	—	1–2	—
Brass rod	30	72 (at least)	80–100	—	—	Chemical analysis
Brass castings	—	—	60–100	—	—	—
Copper (switch contacts)	—	—	75–95	—	—	—
Copper (commutator)	—	—	80–100	—	—	—
Copper (springs)	—	75 (at least)	—	—	—	—
Copper wire	—	—	—	—	—	Conductivity and inspection
Bearing bushes	—	—	70–90	—	—	Chemical analysis
Solder	—	—	—	—	—	Chemical analysis
Key steel	35–45	—	—	—	—	Chemical analysis

Slate and Marble.

The dimensions of the slabs should be checked, the tolerance being $\frac{1}{16}$ in. for the larger slabs. Cracks can quickly be detected by wiping over the slab with a quickly evaporating liquid. The presence of impurities can be tested for by applying to the surface two pointed electrodes connected to a 2,000-volt transformer.

Procedure on Delivery.

It is of little use to test a delivery if after the tests are complete it is found that the material has all been used, or has been mixed with the old stock. The time taken to test should be reduced to a minimum, not only on account of any inconvenience that may be caused but also to reduce the storage space. One method of fulfilling these conditions is as follows: All deliveries on arrival at the works are placed in a

special store. The receipt note is made out and samples are taken for test. A description of the sample with particulars of the supplier, date, order number, works order number, receipt note number, and ultimate destination, are all entered in triplicate in a book which is sent with the samples to the testing department. The samples are here stamped with a serial number which is also entered in the book, and the particulars are noted in a book kept for the purpose. The top copy is signed and serves as a receipt to the storeman. The other two copies are torn out. One of these, a card, is handed with the samples to the man responsible for the tests. He notes on the back of the card the tests performed and, when the tests are complete, returns the card and the results of the tests to the office. The orders to the receiving stores are now written on both the card and third slip, and the third slip is returned to the receiving clerk, who initials the receipt note. The delivery, if accepted, is passed on to the stores. If the delivery does not reach the specification standard, it is generally rejected and returned to the supplier, but sometimes in special cases it may be accepted, perhaps with a proviso that it is not to be used for a certain class of work. This latter course should be used only in cases of emergency, owing to the complications introduced in the stores. The results are now typed and copies are sent to the persons interested. One copy is filed according to the material; and another, together with the card and all figures taken, is filed under the serial number.

Conclusion.

All the plant described in the paper would probably not be installed in any one works. A suitable selection depends on the particular requirements of the works and the resulting economies that are expected. If the apparatus is also to be used for research work, as is often the case, it will be much more elaborate than if used merely for routine testing. Much work has been done in connection with the testing of metals, and the various tests have been standardized. Little progress has been made, however, in regard to the insulating materials, and every manufacturer has his own standards; but this state of affairs will probably be remedied in the near future.

PROCEEDINGS OF THE INSTITUTION.

686th ORDINARY MEETING, 2 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

Mr. J. S. Highfield, Past-President, took the chair at 6 p.m.

The minutes of the Annual General Meeting of the 25th May, 1922, were taken as read, and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

The following donations were announced as having been received and the thanks of the meeting were accorded to the donors :—

Benevolent Fund : F. W. D. Adcock; Anonymous; C. T. Allan; W. F. Andrews; A. G. Barnard; J. E. Baty; H. P. Bearcroft; C. A. Beaton; P. L. Bernstein; J. E. Betley; C. G. Bevan; L. Birks; W. Birmingham; H. E. Blackiston; W. H. Bray; R. V. Broberg; W. Brownlie; E. A. Buxton; H. G. Cameron; A. S. Campbell; P. G. Campling; G. W. Carpenter; F. D. Chadwick; S. K. Chatterjee; J. C. Clarke; J. R. Clayton; G. D. Clegg; H. W. Cockerill; R. L. Cribbes; A. F. Cross; C. F. Crymble; T. E. Daniel; J. F. Davie; H. O. Davies; J. N. Deas; A. C. de Oliveira; The Diesel Engine Users' Association; G. W. Dumbrell; W. Duncan; F. J. Edgar; G. J. Evans; A. R. Everest; L. J. B. Forbes; C. F. Fowler; C. S. Franklin; J. R. Gardiner; E. L. Glew; J. R. W. Grainge; F. W. Green; J. D. Green; J. G. Griffin; E. Halton; C. Hamilton; F. Harris; H. H. Harrison; A. T. Harrop; F. de B. Hart; R. S. Hobson; E. H. Hooper; J. W. Horner; W. Howes; P. R. Hughes; V. R. Hurle; W. H. M. Kelman; P. C. Kerr; C. D. King; F. A. Lawson; T. F. Lee; A. E. McColl; F. C. Meaby; A. P. Mitchell; F. Morton; J. Mullin; A. R. Murray; J. Y. Nelson; C. A. Newell; W. H. Parker; L. W. Phillips; E. A. K. Picard; H. V. Pointon; F. C. Porte; S. C. Price; C. W. L. Ray; W. J. Rickets; A. J. Roberts; A. S. Robertson; E. G. Ross; A. Rushton; J. Russell; A. H. Selwyn; J. W. Slorach; J. L. Smith; E. Steadman; A. Stewart; W. G. Stock; D. Stringfellow; C. F. Thomas; H. J. S. Thomas; G. Thompson; J. A. Troughton; E. O. Turner; F. Walker; L. G. Walker; H. K. Whitehorn; H. W. Wilkinson; E. Williams; J. C Wrighton; The "Twenty-Five" Club; Western Centre (per W. Collins).

The following letter, dated 29th October, was read from the President of the French Society of Electricians :—

DEAR MR. PRESIDENT,

The invitation which you have sent me, on behalf of the Institution of Electrical Engineers, to attend their Meeting on the 2nd November is highly appreciated by the French Society of Electricians as a mark of sympathy and scientific esteem, coming from the illustrious Society over which you preside and addressed to a younger Society which is endeavouring to serve science and industry as well as its country and Allied Nations. I deeply regret not being able to come to London to express to you personally, in the name of the French Society, the cordial feeling of the French electricians towards their colleagues of the United Kingdom and to hear the instructive address which you propose to give. I beg you to convey to the members of the Institution an expression of the warm esteem of their French colleagues and to accept for yourself, Mr. President, my cordial and fraternal sentiments.

(*Signed*) M. BRILLOUIN.

The Premiums (see vol. 60, page 528; also *Institution Notes*, No. 34, page 25, August 1922) awarded during the session 1921–22 were then presented by the Chairman to such of the recipients as were present.

The Chairman: I now have great pleasure in asking the new President, Mr. Frank Gill, to take the chair.

The chair was then vacated by Mr. J. S. Highfield and taken by **Mr. Frank Gill** amid applause.

Mr. Roger T. Smith: It is my privilege to propose a vote of thanks to our retiring President who, in common with his predecessors, will look back upon his year of office with mixed feelings. First of all, the retiring President feels very much as a boy does when he leaves school and goes home for the holidays, and perhaps that is the predominant feeling. I believe that most Presidents—and certainly I know that Mr. Highfield had that feeling—soon after their installation in the chair come to feel that perhaps the greatest possession which the Institution has is its tradition. We in this country cherish our great traditions. We date our civil liberties from the time of King John and, although the electrical industry cannot boast of such an age, the Institution of Electrical Engineers has 50 years of tradition to give it ballast. Perhaps Mr. Highfield will agree that the most interesting events in his year of office were the Commemoration Meetings to celebrate that 50 years' existence. During those Meetings and the social functions which made them so pleasant he was unfortunately confined to his house. Possibly the greatest tribute to his complete understanding of the things and people which go to make up tradition, was the fact that before he fell ill the arrangements made were so complete and so entirely in the proper spirit that, in spite of his absence, the Commemoration Meetings were completely successful. During his period of office not only did he maintain the traditions of the Institution, but he added to them. To give only one instance, I would refer to the way in which, after months of very arduous toil, he succeeded in persuading Mr. Oliver Heaviside to accept the Faraday Medal. Without the President's unfailing courtesy and patience I do not think that this Institution would have had the pleasure of honouring, however late, that very remarkable man. I beg to propose: "That the best thanks of the Institution be accorded to Mr. J. S. Highfield for the very able manner in which he has filled the office of President during the past year."

Mr. Ll. B. Atkinson: It is with very great pleasure that I second the resolution proposed by Mr. Roger Smith. When, at the end of last Session, I handed over the reins of office and vacated the chair in favour of Mr. Highfield, I expressed my full anticipation of the results that would be obtained under his leadership, and I am sure everybody will agree with Mr. Roger Smith that the past Session has been one of the most interesting and enjoyable that it has been our lot to have. Every Session has its problems and its own special tasks, and I should like to refer to one of them, i.e. the completion and dedication of the Institution War Memorial. There are, of course, in an Institution like this, many different thoughts on such subjects, but I think that the War Memorial in its design and wording, and the dedication ceremony in its form and sentiment, were sufficiently wide to cover all the various shades of thought. Those larger matters to which Mr. Roger Smith has referred and which come to the view of the general membership are, as it were, only the peaks in the midst of a very large amount of work which the President has to perform. The ordinary daily work of the Institution involves discussions and decisions which have to be taken daily and hourly by the President on behalf of the members, and there are many occasions when it is very easy to make a mistake which will mar the work of the Institution and destroy its usefulness and popularity among its members. The tact and judgment which the President has shown on those smaller matters as well as on the larger ones have been a great asset to the Institution, and I have much pleasure in seconding the resolution.

The President: Before I formally put this vote to the Meeting, I should like to pay my tribute of admiration to our retiring President. I have seen a good deal of him during the past Session and I have seen that with untiring energy and great ability he has devoted himself to the furtherance of the progress of the Institution. With patience and tact he has dealt with the affairs of the Institution, both in the Council and out of the Council, and he leaves the chair not only with very greatly added respect, but with something which I venture to think is much more valuable—the affection of those whose pleasure it has been to work with him during this past year.

The resolution was then put by the President and carried with acclamation.

Mr. J. S. Highfield: It is very difficult to thank you all for your very kind, your very hearty response to this resolution; indeed it is difficult to say anything after the very kind things that have been said this evening. Mr. Roger Smith said that he felt like a schoolboy when he had given up the office of President; I am not at all sure that I did not feel rather like a schoolboy throughout the whole year. I do not remember a more pleasant year; it was spoilt only by the illness which prevented my attendance at our Commemoration Meetings. It is necessarily pleasant to act as helmsman to this great Institution. It is an

Institution in which I think its members every year individually take greater pride, and its efficiency and influence have been increasing for years past. A good deal was accomplished in the year, thanks in a great measure to the fact that we had become thoroughly re-established in our own building, and also to the way in which everyone helped and worked in the interests of the Institution. The Past-Presidents, particularly the two immediate Past-Presidents, Mr. Roger Smith and Mr. Ll. B. Atkinson, gave help at all times; and it is due to the four Vice-Presidents that the Commemoration Meetings were so admirably conducted and, in addition, there were Members of Council serving manfully on the many Committees. I should also like to mention the Chairmen of the Local Centres and of the Committees who worked very hard and accomplished much. I should like specially to refer to the Chairman and the Committee of the Scottish Centre, and I am sure all the members who took part in the Scottish Meeting will long remember it as a most delightful and useful time. It only remains for me to thank the Secretary and his staff for all the help they gave. They were to me a complete, thoroughly efficient working crew, and all I as helmsman had to do was to take charge of the helm and leave them to do the rest. In conclusion I should like to wish Mr. Gill all the success as our President which I know he will achieve.

The President then delivered his Inaugural Address (see page 1).

Sir John Snell: I should like as my first duty to add to what has been said by our immediate Past-President in offering our congratulations to Mr. Gill on becoming President of this Institution, but I should also like to congratulate the Institution itself upon the appointment as President of one who is a master of his subject. The Address is one of more than national importance, dealing as it does with what the President has happily termed the "transportation of intelligence"; it is perhaps even more than one of Imperial importance because it is cosmopolitan and is on a subject of immense value to the present state of highly organized civilization. Some 10 years ago the President and I were engaged in a very lengthy duel, which entailed our attendance in a stifling court and proved very exhausting to both of us. Sitting there day after day, hearing Mr. Gill unfold the technicalities of the case which he was defending, I became more and more imbued with a deeper and deeper respect for him. After those laborious days, when the judges and others had retired during the long vacation, it fell to the lot of Mr. Gill and myself to sit down day by day to try to arrive at a certain valuation which was entrusted to us. On the one side there was a man who was a master of his subject, who knew every detail from complicated telephone switchboards and large multicore cables down to what are commonly known as "potheads," and on the other side a man who had a most superficial knowledge and who had to rely on the able engineers of the Post Office for their assistance, but Mr. Gill did not take the slightest advantage of this fact throughout the whole of that difficult technical negotiation. My respect for him, which had deepened during those laborious days in Court, reached its acme when we had concluded that work of ours in the long vacation. I suggest that the Address to which we have listened to-night is of the greatest importance, and I think it is more pleasing perhaps to the Institution that, after a succession of Presidents who have represented more particularly the power side of engineering, we should now have an Address representing what is generally known as the weak-current side, delivered by one who has his subject at his finger-ends. The weak-current side is one of increasing importance to the whole world, and one which has not reached in Europe that degree of excellence which it has reached in the home of its birth, the United States. It has become a highly technical branch of our industry Those who have watched the almost uncanny working of an automatic telephone would agree with me there. It is pleasing to think that we now have amongst our Presidential Addresses a paper dealing with long-distance communication. I commend the paper to the members of the Institution and I beg to move "That the best thanks of the Institution be accorded to Mr. Frank Gill for his interesting and instructive Presidential Address, and that, with his permission, the Address be printed in the *Journal* of the Institution."

Sir Richard Glazebrook: I am privileged to second the proposal that has been so ably put before you by Sir John Snell, and I think I need add little to what he has said as to the merits and the work of our President and the importance that we attach to the fact that he is now President of the Institution and in a position to give us something of the vast stores of his knowledge on this very complicated and difficult subject. I would ask you to thank him for his Address, not merely for the Address itself but for the high ideals that he put before us as to the manner in which he would undertake the work of President and in which we as members should discharge our duties, and for his realization of the importance of those duties. One could spend a long time in discussing the advantages to civilization derived from the work of engineers, and there are few details of that work that have added more to the advantages of life and to the progress of civilization than the improvements in the method of communication about which we have heard so much this evening. We thank him for the instructive character of the Address, which has been really instructive in many ways. We all have some idea of the complication of telephonic communication, the difficulties that must occur, and the problems that the telephone engineer has to solve, but I think that our knowledge—my own at least—has been comparatively small, and I believe that few of us realized all the skill and thought that must have been put into the development of telephony as we now know it and as it is in the United States. In other ways I think the Address is instructive because it has put clearly before us the great importance of this problem of long-distance telephony and has indicated some methods by which a solution of the problem in Europe might be possible.

The resolution was then put to the meeting by Mr. J. S. Highfield, Past-President, and was carried with acclamation. After the President had briefly replied, the meeting terminated at 7.35 p.m.

OBSERVATIONS OF THE FIELD STRENGTH OF HORSEA WIRELESS STATION.*

By E. B. Moullin, M.A.

(*Paper received* 18*th September*, 1922.)

Summary.

Many measurements are recorded of the strength at Cambridge of the signals from Horsea during September 1921, in which the Vallauri method of measurement was employed. The field strength is deduced from the measured E.M.F. of the signal, the effective height of the receiving aerial being determined experimentally both from the distribution of current in the aerial up-lead, and by comparing the receptive power of the aerial with that of a loop. Incidentally, the measurements of effective height provide a very accurate verification of the law that for short distances the E.M.F. set up in an aerial is in direct proportion to the frequency of the incident waves. It is found that at a wave-length of 3 000 m the Horsea signals suffer in their journey an absorption of 40 per cent, and evidence is produced of a regular diurnal variation of intensity. The accuracy of the aural method of comparison is discussed, and the feasibility of making long-distance measurements with a visual indicator, instead of by aural comparison, is pointed out.

Table of Contents.

(1) Introduction.

In August, September and October, 1921, the Naval Wireless Station at Horsea, Portsmouth, carried out a series of regular continuous-wave transmissions. Information of the tests was kindly afforded to the author by Mr. L. B. Turner, of the Wireless Telegraphy Commission, and advantage was taken of this excellent opportunity to make systematic observations of the field strengths.

The transmissions were on wave-lengths ranging from 2 500 m to 8 000 m, and were distributed throughout a continuous 24 hours at intervals of a few days.

The author's experiments described in the paper were made during the end of August, early September and early October at Cambridge, which is situated 177 km N.E. by N. of Horsea. This distance is among the longest recorded of the short-distance overland tests, and it was hoped that the measurements could be used as a still further test of the Hertz formula, without any correcting factor for absorption. The results, however, show field strengths some 40 per cent less than the value given by the Hertz formula, owing to absorption by the intervening land and obstructions. The path from Horsea to Cambridge lies over the Portsdown Hills, the hills near Guildford and, finally, after a long stretch of flat, open country, over the low chalk hills near Baldock, some 15 miles from Cambridge. During the whole period of the measurements the weather was exceptionally hot and fine, and had been so for the previous three months.

(2) Method of Measuring the Received E.M.F.

The method employed was a slight modification of the well-known comparison method due to Vallauri. This system of signal measurement has often been described, but may be briefly summarized as follows:

Two identical receiving loops are provided having their planes at right-angles to one another, and oriented so that the effect produced in one is a maximum, and in consequence a minimum or zero in the other. The receiving circuit with its amplifiers and detectors can be connected at will to either loop, and a local E.M.F. of the same frequency as the incoming signal and of adjustable and measurable value can, when desired, be introduced into the circuit comprised by the receiver, and the loop that is inappreciably affected by the incoming signal. It will be understood that there are two circuits identical in every respect, in one of which is situated an E.M.F. produced by the incoming electromagnetic waves radiated from a distant transmitting station, while in the other is situated an E.M.F. of the same frequency but produced by a local generator.

If the local E.M.F. produces the same current in its associated circuit as the signal E.M.F. produces in the other circuit, then, the circuits being identical, the locally produced E.M.F. is equal in value to the E.M.F. produced by the incoming signal. The signal E.M.F. having been determined in this way, the field strength can be calculated from the linear dimensions of the receiving loop.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

The currents produced by either E.M.F. can be measured and compared by using a thermo-junction, by measuring the rectified current produced by a valve connected across part of the circuit, or by comparing the sounds produced in a telephone connected to this rectifier: the choice of method depends mainly on the magnitude of the current to be measured.

The difficulties of the Vallauri method of measurement are well known, but probably only fully recognized by those who have actually performed the operation. The two main difficuties are (1) comparing the effect of the signal and local E.M.F., and (2) the measurement of the local E.M.F. The former difficulty is most accentuated when audible comparison has to be resorted to. If the incoming waves are broken up into Morse signs, then audible comparison is the only satisfactory method, but it is unfortunately under these circumstances that audible comparison becomes most difficult. If the transmitting key is held down it is easy to match perfectly the note of the local signal with that of the incoming signal, the condition necessary both to ensure that the local E.M.F. is of the correct frequency and to make accurate comparison possible. But when Morse signs are being received, as was the case with the Horsea transmissions, it is in general impossible to match their note with that of the locally produced Morse signs nearer than a semitone; this is possibly due to the transmitting station and local generator having different decrements, even though the two receiving circuits have the same decrement. Any small difference of note entails constant worry as to whether the local generator is adjusted to the correct frequency.

The difficulties attendant upon the measurement of the local E.M.F. are those involved in designing suitable means (e.g. inductive, capacity or resistance coupling) for introducing it into the required circuit, and more especially in effectively screening, both magnetically and electrically, the whole of the local generator circuit in order to ensure that no E.M.F. is introduced except through the known and desired path.

The author's experiments differ from those of Vallauri in that instead of using two suitably oriented loops, the incoming signal produced an E.M.F. in a small, flat-topped aerial; the local E.M.F. was introduced into an equivalent circuit built up so as to have the same electrical constants as the actual aerial, but of linear dimensions so small that the effect upon it of the incoming signal was infinitesimal.

(3) Description of the Aerial used, and the Method of building up the Equivalent Circuit.

The aerial employed consisted of two parallel wires 1 m apart and 21 m long, stretched parallel to the ground at an average height of $5\frac{1}{2}$ m. Each conductor consisted of two No. 20 S.W.G. copper wires stranded together, and the steady-current resistance of the whole was about 0·25 ohm. The earth connection was to a water pipe close to the receiver.

The aerial was supported at one end from the gable of a house and at the other by an earthed, tubular-steel mast, the clearance at each end being about 1 m. The arrangement of the up-lead can be seen from Fig. 5.

The static capacity of the aerial was found by a bridge measurement to be $310\,\mu\mu$F. The natural wave-length was not accurately determined, but would probably be about $4\frac{1}{2}$ times the total length of wire or, say, 150 m. Extrapolation from a curve connecting wave-length and inductance inserted in the aerial indicates that the fundamental was about 170 m: the total inductance of the aerial must have been between $30\,\mu$H and $60\,\mu$H.

The circuit used for receiving is shown in Fig. 1. The inductance L was fixed and equal to $2\,000\,\mu$H $\pm$ 2 per cent, and the capacity C varied between $600\,\mu\mu$F for $\lambda = 2\,500$ m up to $3\,400\,\mu\mu$F for $\lambda = 5\,000$ m. The resistance of L ranged from 26 ohms at 3×10^5 periods per sec. down to 14 ohms at $1{\cdot}5 \times 10^5$ periods per sec. (steady-current resistance 13 ohms).

A triode rectifying by curvature of the anode-current characteristic was employed for detecting, with the grid 4-volt negative to prevent decrement due to grid current. Any form of retro-action was carefully avoided, and a separate heterodyne used to render the signals audible.

It was assumed that the circuit of Fig. 1 with a

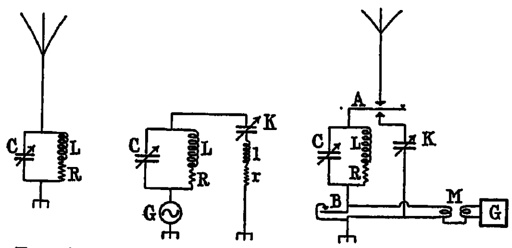


Fig. 1. Fig. 2. Fig. 3.

distributed E.M.F. in the aerial could be replaced by the circuit shown in Fig. 2 acted upon by a concentrated E.M.F. produced by the generator G.

If L is greater than l and C greater than K, the condition which makes the P.D. across L as great as possible for a given E.M.F. supplied by the generator is, to a close approximation, given by

$$\omega^2\{L(K + C) + Kl\} = 1$$

For the values of L, l, K and C employed, this expression is correct to about 0·2 per cent. It was found that, with l omitted from the circuit of Fig. 2, the value of K required to tune the circuit of Fig. 2 to the same frequency as the actual aerial circuit in Fig. 1, ranged from $220\,\mu\mu$F for $\lambda = 2\,000$ m up to $270\,\mu\mu$F for $\lambda = 6\,000$ m. Introducing a small inductance first in the aerial up-lead, and then in series with K, seemed to change the frequency of both circuits by the same amount; it was in consequence considered that no appreciable error would be introduced by omitting l from the equivalent circuit. If l/L is about 1/20, then it is easy to show that K is about 5 per cent greater than it would have been if l had not been omitted. It was hoped that it would have been possible to find the appropriate value of r by comparing the sound produced in the telephones when the same local

E.M.F. was introduced in turn into the true aerial circuit and into the equivalent circuit; but the circuits appeared to be so nearly equal, even with r entirely omitted, that it was decided not to attempt to replace the resistance of the aerial. It can be shown that the presence of a resistance r in the equivalent circuit reduces the P.D. across L in the ratio

$$\frac{R(K+C)}{K} \text{ to } \left\{\frac{rK}{K+C} + \frac{R(K+C)}{K}\right\}$$

It can be seen from this expression that with the values of K and C in use, the presence of r does not appreciably reduce the P.D. across L unless $r \gg R$. By using a form of the author's thermionic voltmeter* to determine the P.D. across L, it has subsequently been found that a given E.M.F. produced a P.D. across L 15 per cent greater in the equivalent circuit than in the actual aerial circuit. The table of Section 6 shows the value of the signal E.M.F. as actually determined without allowance for the aerial resistance, and also the value corrected by 15 per cent.

(4) Production and Measurement of the Local E.M.F.

A triode oscillator completely enclosed in a metal case, placed about 6 ft. away from the receiver, was used as the local generator. The E.M.F. was introduced from this generator into the equivalent circuit by means of mutual inductances the values of which could be calculated. The generator current passing through the primary of these mutual inductances was measured by a 1-ohm vacuo-thermo junction and reflecting galvanometer, the junction being calibrated with direct current. The mutuals used, four in number, took the form of two co-axial circles of fine wire with planes parallel and placed about 0·5 cm apart. The calculated values were as follows: $M_1 = 0{\cdot}180\,\mu$H; $M_2 = 0{\cdot}48\,\mu$H; $M_3 = 0{\cdot}78\,\mu$H; and $M_4 = 0{\cdot}24\,\mu$H. The current through the primary of these mutuals was varied by altering the output of the triode generator by means of a variable-resistance box (shunted by a condenser) placed in the anode circuit: a more convenient method would probably have been to shunt the primary of the mutual inductance itself with a variable resistance.

(5) Method of Adjusting the Circuits and Making Comparisons.

The aerial circuit and the equivalent circuit used are shown in Fig. 3. By depressing the key A the aerial was replaced by the condenser K, and by depressing the short-circuiting key B the local E.M.F. could be introduced into the aerial or into the equivalent circuit.

Having picked up the incoming signal and adjusted the condenser C until the sound produced in the telephones, actuated by the rectifier connected across L, was a maximum, the heterodyne was adjusted until the beat note became so low as to be inaudible. The frequency of the local generator G was then adjusted until, with the keys A and B depressed, the beat note between it and the heterodyne became inaudibly low; the local generator and the incoming signal were then sensibly of the same frequency. The heterodyne was then altered so as to give a fairly high-pitched note with the signal: fine adjustment was then made to the frequency of G to match its note to the signal. This method of adjustment was found in practice to be the most reliable, and prevented any chance of having the frequency of G as much above the heterodyne as the signal was below, or vice versa. On a few occasions the Horsea key was held down for a short space at the end of a sending period, and more than once it was found that the Horsea note and the local note caused beats of only a few periods per second, which seemed to justify the method.

Having made a preliminary adjustment of the output of G, the telephones were moved off the ears, or the detecting triode dulled, until the Horsea signals were on the limit of audition. G was then finally adjusted until the local signals were also just audible.

Having noted the current through the primary of the mutual inductance, a second mutual inductance of very different value was substituted for the first, and the comparison repeated. Occasionally, when time permitted, a third measurement was made with a third mutual inductance.

The importance of these check measurements is two-fold.

(1) If the two measurements are not in fairly close agreement, it shows that the mutual inductance is not the only path through which the local E.M.F. is being introduced.

(2) If previous experiments have shown that the local generator is effectively screened, then a check is made on the accuracy of the comparison, at best a difficult operation.

Between 23rd August and 2nd September, 1921, 37 measurements were made, all of which were useless owing to defective screening. The various causes of unsuccessful screening were traced out one by one, until on 4th September measurements with three mutual inductances showed that success had at last been achieved.

The following examples are given to show that the E.M.F. was introduced through the desired path, and to show also that the comparison can be made with an accuracy of at least $\pm$ 10 per cent. I denotes the current through the primary of a mutual inductance M.

4th September. $\lambda = 4\,500$ m; $M_1I_1/M_2I_2 = 1{\cdot}08$
21st October. $\lambda = 3\,000$ m; $M_2I_2/M_3I_3 = 1{\cdot}12$

On 7th September a comparison was made with a signal produced by a local continuous-wave generator, with key held down to aid comparison, the result being that with $\lambda = 3\,000$ m, $M_1I_1/M_2I_2 = 1{\cdot}12$.

The author would suggest that in measuring signal strengths it would be an advantage to make a general practice of using several mutual inductances, or some equivalent plan of obtaining check measurements; there could then be no doubt that the measured E.M.F. was a fair approximation to the signal E.M.F.

* See paper read before the Wireless Section, 6th December, 1922; also *Wireless World*, 1922, vol. 10, p. 1.

TABLE 1.

Date and time	Transmitting current	Wave-length	M_2I_2	M_3I_3	Received E.M.F. (= ωMI)	Received E.M.F. (× 1·15 to correct for aerial res.)
	A	m	μH × mA	μH × mA	mV	mV
19/10/21						
2000	50	4 500	0·48 × 12 = 5·76	—	—	—
21/10/21						
0750–0800	51	3 000	0·48 × 16·7 = 8·00	—	5	5·6
1500–1522	48	3 000	0·48 × 16·7 = 8·00	—	5	5·6
1538–1600	49	3 000	0·48 × 16·0 = 7·70	—	4·85	5·3
1900–1922	49	3 000	0·48 × 16·0 = 7·70	—	4·85	5·3
1938–2000	50	3 000	—	0·78 × 8·4 = 6·6	4·1	4·7
2100–2122	49	3 000	0·48 × 15·1 = 7·25	0·78 × 8·0 = 6·2	4·55 or 3·9	5 or 4·5
2138–2200	50	3 000	0·48 × 14·6 = 7	0·78 × 8·0 = 6·2	4·4 or 3·9	5 or 4·5
			Mean 7·6	Mean 6·3	4·8 or 4·0	5·5 or 4·6
Reversion to incorrect circuit for check purposes.						
1500–1522	48	3 000	0·48 × 5·5 = 2·65	0·18 × 8·9 = 1·6	—	—

TABLE 2.

Date and time	Transmitting current	Wave-length	M_1I_1	M_2I_2	M_4I_4
	A	m	μH × mA	μH × mA	μH × mA
6/9/21					
0700–0722	37	2 500	—	—	0·24 × 9·3 = 2·24
0900–0922	37	2 500	—	0·48 × 6·7 = 3·2	0·24 × 9·7 = 2·34
1100–1122	37	2 500	—	0·48 × 6 = 2·9	—
1300–1322	38	2 500	—	0·48 × 5·7 = 2·75	0·24 × 8·6 = 2·05
1500–1522	39	2 500	—	—	0·24 × 7·5 = 1·8
1700–1722	42	2 500	—	—	0·24 × 7·7 = 1·85
1900–1922	40	2 500	0·18 × 9 = 1·56	—	—
2100–2122	38	2 500	0·18 × 9 = 1·56	0·48 × 4·2 = 2	—
			Mean 1·56	Mean 2·7	Mean 2·05
11/10/21					
1900–1922	37	2 500	0·18 × 8·4 = 1·5	0·48 × 4·3 = 2·05	—
2100–2122	38	2 500	0·18 × 7·5 = 1·35	0·48 × 4·0 = 1·90	—
14/10/21					
1910–1922	52	2 500	—	0·48 × 5·0 = 2·40	—
11/10/21					
2140–2200	36	3 000	0·18 × 9·5 = 1·66	0·48 × 3·5 = 1·68	—
14/10/21					
1945–1955	50	3 000	—	0·48 × 5·0 = 2·40	—
2145–2200	51	3 000	0·18 × 9·8 = 1·76	0·48 × 4·7 = 2·20	—
18/10/21					
2115–2122	45	3 000	0·18 × 8·5 = 1·52	—	—
2145–2200	45	3 000	0·18 × 8·1 = 1·48	0·48 × 4·5 = 2·15	—
4/9/21					
2015–2045	48	4 500	0·18 × 10·5 = 1·9	0·48 × 3·5 = 1·70	—
5/9/21					
2015–2045	50	4 500	0·18 × 10·6 = 1·9	0·48 × 5·0 = 2·40	0·24 × 7·1 = 1·7
6/9/21					
2015–2045	50	4 500	0·18 × 9·8 = 1·76	0·48 × 4·2 = 2·00	—
7/9/21					
2015–2045	50	4 500	0·18 × 10·5 = 1·9	0·48 × 4·6 = 2·20	—

(6) TABLES OF MEASURED E.M.F.'s.

On 19th and 21st October, 1921, 12 measurements were made, and are shown collected in Table 1.

Between 4th September and 18th October, 1921, 33 measurements were made, and are shown collected in Table 2.

The signal E.M.F. cannot, unfortunately, be deduced from the values given in Table 2. Owing to a misconception, a mistake was made in the equivalent circuit, K being placed in parallel with C instead of in series with L and C in parallel: the E.M.F.'s obtained from Table 2 differ from the signal E.M.F. by some constant dependent on the values of C and K. The readings, though useless for determining the values of the signal E.M.F., are perfectly valid for comparison purposes.

(7) MEASUREMENT OF THE EFFECTIVE HEIGHT OF THE AERIAL.

In order that the value of the incident magnetic or electric field may be deduced from the measured E.M.F. in the aerial, the effective height of the aerial must be determined.

Suppose the distribution of current in the up-lead of

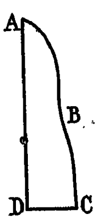
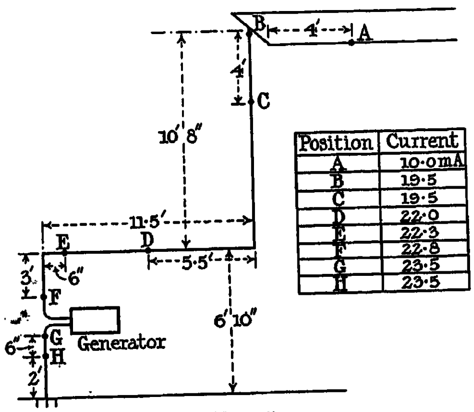


FIG. 4.



Position	Current
A	10·0mA
B	19·5
C	19·5
D	22·0
E	22·3
F	22·8
G	23·5
H	23·5

FIG. 5.

the aerial to be as shown in Fig. 4; then the aerial is equivalent to a uniform vertical current of height equal to (area ABCD/CD). In the case of an aerial having a large-capacity top, the equivalent height approximates closely to the actual height of the roof. Under the ideal conditions of a perfectly conducting earth and of no local screening due to currents induced in surrounding objects, the effective height of the aerial would be equal to the equivalent height as defined above.

The equivalent height of the aerial under consideration was measured by plotting a curve of current distribution in the up-lead, determined by placing a thermo-junction at the points marked A, B, C, D, E, F, G and H in Fig. 5. The resulting curve of current distribution is plotted in Fig. 6. That a large-capacity top is indeed successful in producing a sensibly uniform current in the up-lead is readily seen from this curve, which shows that the equivalent height (4·8 m) is 90 per cent of the actual height.

As the bottom 2 m of the up-lead were inside a house, it seemed probable that the effective height would be less than 4·8 m, on account of local screening. The effective height was determined by comparing the E.M.F. set up in the aerial with that set up in a loop; the transmitting station being the same in each case and situated 1 000 m N.W. of the aerial.

The comparison was not made audibly, but by using a form of the author's thermionic voltmeter actuated through a two-stage amplifier connected across the aerial tuning inductance.

The method of measurement consisted in noting the voltmeter deflection produced by the incoming signal, and then introducing into the earth lead an E.M.F. of the same frequency and adjusting its magnitude until the same voltmeter deflection was produced. In this way, as with the Aldebaran experiments of the Marine Française, the local E.M.F. is introduced into the actual aerial circuit, and there is no necessity to produce its equivalent.

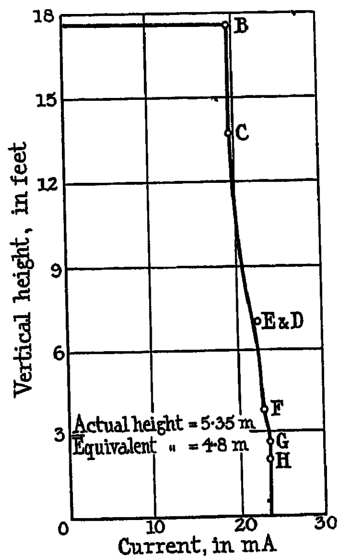


FIG. 6.

The local E.M.F. was not introduced through the medium of a mutual inductance, but by means of a resistance potentiometer constructed from fine Eureka wire, the current through the potentiometer wire being measured by a sensitive vacuo-thermo junction. This system has many advantages to offer over the mutual inductance method, first because it is easier to construct a small resistance than to construct a small mutual inductance of the value required; secondly, the measurement of very small mutuals is a matter of no little difficulty, and few formulæ are available for calculating the values of a variable mutual inductance of suitable size and dimensions. The resistance potentiometer is readily made with a slide wire so as to be completely adjustable. The local E.M.F. can then be adjusted by varying the slide rather than by the amount of current passing through it. Check measurements can be performed, as with a fixed mutual inductance, by making two measurements with different slide currents.

The signal E.M.F. produced by 0·42 A in the sending aerial was measured at wave-lengths of 1 920 m and 1 020 m, also at 1 020 m with 0·23 A in the sending

aerial. The results are shown collected in Table 3. Each of the three tests was repeated six times, and the values tabulated are the mean of the six readings: in no case did a reading depart more than 2 per cent from the mean value given.

Fig. 7 shows voltmeter deflections plotted against the value of the locally impressed E.M.F. This curve was taken directly after the test at 1 920 m wave-length, and as it is a straight line through the origin, it shows that no E.M.F. was introduced through any other path but the potentiometer. Similar curves, equally good, were taken after each of the 1 020 m wave-length tests.

TABLE 3.

Wave-length	Transmitting current	Mean voltmeter reading	Received E.M.F.	$\lambda E/I_s$
m	A	V	mV	
1 920	0·4	1·01	1·11	$5{\cdot}35 \times 10^3$
1 020	0·42	1·63	2·15	$5{\cdot}25 \times 10^3$
1 020	0·23	1·45	1·2	$5{\cdot}3 \times 10^3$

Note.—The amplifier adjustment was different in each case.

Table 3 shows that for the same transmitting current the received E.M.F. varies inversely as the wave-length, and that the E.M.F. for the same wave-length varies directly as the transmitting current. This shows that,

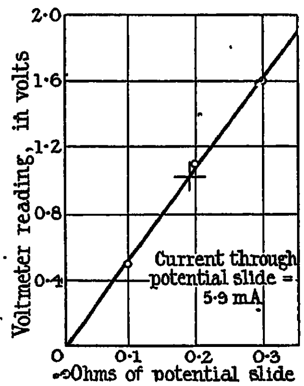


FIG. 7.

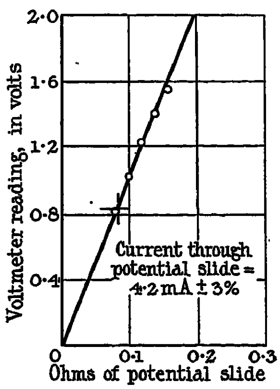


FIG. 8.

at any rate between 1 000 m and 2 000 m wave-length, the effective receiving height is independent of frequency.

The receiving loop was constructed by removing one of the two wires forming the top of the aerial, and bringing a wire from the far end down the mast and back again along the ground to the instruments.

The current in the transmitting aerial was 0·43 A at a wave-length of 1 020 m, and the mean voltmeter reading from seven signals was 0·83 V, with a maximum departure of 2 per cent from the mean.

Fig. 8 shows voltmeter readings plotted against local E.M.F. (as in Fig. 6), from which it may be seen that the signal E.M.F. was 0·34 mV.

The E.M.F. set up in an aerial from an aerial is given by the formula

$$E_a = \frac{188 h_s h_r I_s}{\lambda d} \text{ volts,}$$

and the E.M.F. set up in a loop from an aerial is given by the formula

$$E_l = \frac{1\,184 h_s I_s A \cos\alpha}{\lambda^2 d} \text{ volts}$$

where A is the area of the loop and α is the angle between the plane of the loop and the direction of the transmitting aerial.

If ${}_1I_s$ is the sending current when receiving on the aerial, and ${}_2I_s$ is the sending current when receiving on the loop, λ, d and h_s being the same in both cases, we have

$$h_r = \frac{E_a}{E_l} \cdot \frac{1\,184 \times {}_2I_s A \cos\alpha}{188 \times {}_1I_s \lambda}$$

In the particular case considered $A = 130$ m², $\alpha = 35°$, and $\lambda = 1\,020$ m, hence $h_r = 4{\cdot}25$ m.

The effective height is thus found to be 89 per cent of the equivalent height and 80 per cent of the actual height.

The loop being formed from the aerial, the screening effects obtaining in each case are the same. It was impossible to erect a transmitter in the direction of Horsea, but as the ground in the immediate vicinity was more open in the Horsea direction than in the opposite direction towards the transmitter, the value found for the effective height is more likely to be slightly too low than the reverse.

(8) FIELD STRENGTH PRODUCED BY HORSEA, AND THE CORRECTION FACTOR FOR ABSORPTION.

Table 1 shows that at 3 000 m wave-length the E.M.F. set up by Horsea in the aerial at Cambridge was between 4·6 and 5·5 mV, the effective height of the receiving aerial being 4·25 m. This corresponds to a field strength of about 0·012 mV per cm.

It is believed that the Horsea aerial has a capacity of 4 900 $\mu\mu$F, that the height of the roof is about 130 m, and that the effective height is 113 m.

Under ideal conditions of a perfectly conducting earth and no absorption of the wave from any causes, the electric field intensity set up is given by the formula

$$E = \frac{60\pi h_s I_s}{\lambda d} \text{ volts per cm}$$

In the present case $d = 178$ km, $\lambda = 3\,000$ m, and $I_s = 50$ A, so that the electrical intensity under such conditions would be 0·02 mV per cm; the intensity actually measured is exactly 60 per cent of the ideal. At a wave-length of 4 500 m and the same transmitting current, the electric intensity would be 0·0136 mV per cm. The E.M.F. measured for this wave-length (on 19th October, 1921) was 2·9 mV,* corresponding to 0·007 mV per cm, so that the correction factor for absorption is in this case 0·52.

* For these figures, and for the values of the sending currents, the author is indebted to H.M. Signal School, Portsmouth, through the Wireless Telegraphy Commission.

A correction factor of as much as 0·6 for such a comparatively short overland transmission may seem rather surprising, but is nevertheless not without precedent. The experiments of Reich in 1913 between Cologne and Göttingen*—a distance of 216 km—show a correction factor of 0·61 at a wave-length of 3 000 m, and a correction factor of as much as 0·4 at 2 000 m wave-length. Austin† records a case of a transmission at 1 000 m wave-length over a distance of 83 km over land, in which the correcting factor was 0·45. In both the cases cited above the method of measurement was with a thermo-element placed in the aerial. It is of interest to note that the Austin-Cohen formula for oversea transmission gives a correction factor of 0·86 and the Fuller formula about 0·88. By comparison with these a correction factor of 0·6 for overland transmission does not seem unduly great.

It would be interesting to discover whether the absorption is due mainly to the passage over the first (hilly) half of the path. If measurements of Horsea could be made at the National Physical Laboratory, or some station in that vicinity, they would be very instructive in this respect.

(9) Probable Accuracy of Aural Comparison and Evidence of Diurnal Variation in Signal Strength.

The observations given in Table 2 cannot, unfortunately, be used to determine the value of the field strength, because, as explained before, they give the value of the E.M.F. required to produce the correct copy of the signal in a circuit that was not the correct copy of the aerial; they are too small in some ratio depending on the frequency. This ratio can be determined for the case of the 3 000 m wave, because there were many observations made with both the correct and the incorrect circuit. Unfortunately, as no more signals of 2 500 m wave-length were sent, the conversion factor could not be found for this wave.

The observations of Table 2, though useless for the actual determination of signal strength, are nevertheless perfectly valid for analysing the probable accuracy of aural comparison, and for comparing signal strengths on different days or during the passage of a single day.

Reference to the Horsea log (obtained several months after the measurements were finished) shows that there were only two occasions measured on which the sending currents differed appreciably.

These occurred on 11th and 14th October, and the results are given in Table 4 for ease of comparison.

It will be seen from this table that the E.M.F. measured varies almost exactly as the transmitting current: the extent of the departure from the mean value indicates that the accuracy of the aural comparison must be of the order of ± 5 per cent. In the case of Vallauri's measurements there is a departure of about 12 per cent from the mean in each group of signals recorded. The observations of the press signals (λ = 4 500 m) on each of four consecutive nights show a variation of 5 per cent from the mean.* So as to minimize risk of subconsciously adjusting the local generator until the galvanometer reading coincided with the previous observation, the galvanometer was re-suspended and the scale distance altered before the measurement of the press signal on 5th October, and calibrated after the determination of the signal E.M.F. In spite of these alterations the observations on 4th and 5th October agree very closely. With the same end in view the filament and anode voltages of the local generator were several times altered in order to change the relation between the output of the generator and the adjusting resistance placed in the anode circuit (see Section 4).

In each of the two all-day observations (on 6th September and 9th October, respectively) the extent of the departure of observed E.M.F. from the mean value found seems to have some relation to the hour of observation.

The percentage variation from the mean, plotted against time of observation for these two days, is shown in Fig. 9. It can be seen that the variations from the mean do not occur in a random manner like mere errors of observation. In the early part of the day the signals are always stronger than the mean, and vice versa; also the two curves, taken six weeks

Table 4.

Date and time	Wave-length λ	Transmitting current I_s	M_1I_1	M_2I_2	M_1I_1/I_s	M_2I_2/I_s
	m	A				
11/10/21 2100–2122	2 500	38	$0{\cdot}18 \times 7{\cdot}5 = 1{\cdot}35$	$0{\cdot}48 \times 4 = 1{\cdot}9$	350	500
14/10/21 1910–1922	2 500	52	—	$0{\cdot}48 \times 5 = 2{\cdot}4$	—	460
11/10/21 2140–2200	3 000	36	$0{\cdot}18 \times 9{\cdot}5 = 1{\cdot}66$	$0{\cdot}48 \times 3{\cdot}5 = 1{\cdot}68$	460	465
14/10/21 1945–1955	3 000	50	—	$0{\cdot}48 \times 5 = 2{\cdot}4$	—	480
2145–2200	3 000	51	$0{\cdot}18 \times 9{\cdot}8 = 1{\cdot}76$	$0{\cdot}48 \times 4{\cdot}7 = 2{\cdot}2$	345	430

* *Physikalische Zeitschrift*, 1913, vol. 14, p. 934.

† *Bulletin of the Bureau of Standards*, 1911, vol. 7, p. 315.

* See Table 2.

apart, have the same general characteristics. The difficulties and errors inherent to aural comparison are too great to allow very much reliance to be placed on these curves of temporal variation of signal strength; but they nevertheless suggest that a regular diurnal variation is observable even over comparatively short distances, such as 100 miles. Further observations on this point would be of much interest.

(10) Comparison of Measurements made with Different Mutual Inductances.

Tables 1, 2 and 4 show that the measurements of the same signal with different mutual inductances never agree exactly; that of 0·48 μH is always from 20 to 30 per cent greater than that of 0·175 μH, and 20 per cent greater than that of 0·77 μH.

This discrepancy naturally suggests that there was some other small path by which some part of the signal was introduced, but the author believes that this was not the case, for the following reasons. First, tests were made repeatedly to see if the local E.M.F. was audible without the introducing key B (Fig. 3) being

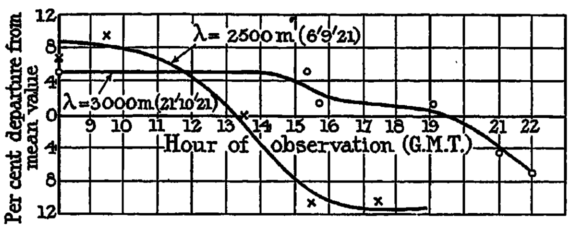


Fig. 9.

pressed; in no case could any sound whatever be heard on the equivalent circuit, and only a very slight trace on the actual aerial. Secondly, the mutual inductance leads were occasionally crossed over and this second determination was always in complete agreement with the first.

The discrepancy is presumably due to the calculated value of the inductance being incorrect (probably due to more than one turn being used), or else to the existence of a capacity coupling in addition to an inductive coupling between the coils of the mutual inductance.

The value of each mutual inductance has been measured and found to be approximately the same as that calculated, but the possible accuracy of the measurements was not sufficient to determine with certainty the ratio between them.

The formula used for calculating the value of the mutual inductance is

$$M = 4\pi a\left(\log_e\frac{8a}{d} - 2\right)n_1 n_2 \text{ cm}$$

where a is the radius of the circle,

d is the distance between the planes of the two circles, and

n_1 and n_2 are the number of turns in each coil.

Particulars of the four mutual inductances are given in Table 5.

Table 5.

Designation of mutual inductance	a	d	n_1	n_2	Value
	cm	cm			μH
1	3·75	0·63	2	1	0·180
2	3·75	0·32	2	2	0·48
3	6	0·5	2	2	0·78
4	2·9	0·38	3	1	0·23

(11) Conclusion.

Although aural comparison is undoubtedly capable of yielding consistent results, it is a most difficult, laborious and tiring operation. Now that thermionic valves are so perfect and easy to use it seems almost unnecessary to resort to aural comparison, since a visual apparatus can be readily arranged and used. Examples of both methods have been given in the paper, and the accuracy and advantages of the indicator method are too obvious to need detailed description: the absence of the necessity for a heterodyne is in itself a tremendous gain.

For measuring extremely weak signals the aural method may be the only one available, but that the visual method is capable of considerable sensitivity the following example will make clear.

It has been seen that it is easy to measure an E.M.F. of only 0·5 mV in an aerial of very high resistance; greater sensitivity can of course be obtained by using more than a two-stage amplifier, but the measurements then become difficult unless the amplification is obtained by several aperiodic stages. If, as has been suggested,* a balanced rectifier is used as the final indicator instead of a direct-calibrated thermionic voltmeter, an additional sensitivity of at least 50 times can be obtained.

If an aerial 42 m high (10 times the height of the Cambridge aerial) is available, by no means an impossible height for a ship aerial, then, according to the Fuller formula, Horsea with a wave-length of 6 000 m would produce in it an E.M.F. of 0·25 mV at a distance of 2 500 miles. Consequently it is possible to proceed right across the North Atlantic with a visual indicator and measure continuously the signal E.M.F. from even a comparatively small station like Horsea.

Should an expedition be arranged for the purpose it could hardly fail to get most valuable and accurate information on the relation between absorption and distance and also on twilight effects.

* E. B. Moullin and L. B. Turner: "The Thermionic Triode as Rectifier," *Journal I.E.E.*, 1922, vol. 59, p. 706.

TELEPHONIC REPEATERS AND LONG DISTANCE TELEPHONY.

By J. A. COOPER, Student.

(ABSTRACT *of paper read before the* SOUTH MIDLAND STUDENTS' SECTION, 17*th January*, 1922.)

SUMMARY.

The paper reviews the development of long-distance telephony and shows the great improvements effected by the introduction of telephonic repeaters employing thermionic valves.

Improvements of greater importance introduced up to April, 1921, when the paper was written, were made by the use of the microphonic transmitter, hard drawn copper wire, loading, cable balancing, phantom circuits and the triode repeater.

The repeater is defined and is shown to have the following advantages: it increases the telephonic range and makes possible the use of finer wire or underground cable. From a consideration of the theory of the triode it is shown that hard valves are preferred because of their longer life and greater stability.

Post Office tests for magnification, speech, stability, life and characteristics are described, and results of some experiments are given.

An account of the Edison, single-relay and double-relay systems is given, and the difficulties encountered in their designs are indicated. The double relay is shown to be preferable on the grounds of adaptability and simplicity.

Results are given, indicating that if repeaters were inserted at intervals equivalent to 15 miles of standard cable or telephone lines an improvement of 15 to 20 m.s.c. would be brought about.

With regard to cost it is stated that a single repeater costs £50 a year to maintain but leads to economy, e.g. a saving of £15 000 a year on London's main trunk lines alone.

Some indication is given as to the probable development of long-distance telephone systems. A forecast of 50-lb. trunk lines, and transcontinental and transoceanic telephony is made.

References are given in the Appendix.

INTRODUCTION.

The telephone engineer regards his long-distance circuits as long-distance power-transmission lines. These lines may vary in length from 2 000 miles to (theoretically) infinity. Unlike ordinary power lines the telephone circuit carries a current of varying frequency, the frequency depending upon the speaker's voice. Again, a few micro-watts are sufficient to actuate a telephone receiver, and to obtain this power at the receiving end a few milli-watts must be generated by the transmitter. An efficiency of less than 1 per cent is indicated. In dealing with a telephone line five factors have to be considered, viz. resistance, insulation, capacity, inductance and its liability to cause, or be affected by, cross-talk and other outside disturbances.

All these factors are intimately connected with each other. For obvious reasons telephone lines have to be run very close together, and this leads invariably to mutual induction or cross-talk. It is of the highest importance that cross-talk shall be eliminated and contractors have to make sure that: "In any completed section of (balanced telephone) cable, the amount of cross-talk between any two circuits shall not exceed that due to 40 millionths of the current entering the cable at the sending end as measured on a standard cross-talk meter." On overhead telephone lines, and in unbalanced cable circuits, the cross-talk may be 10 times as great as that on unbalanced cables. However careful the contractor may be, cross-talk is inevitable unless the current generated by the transmitter is kept at a low value. Hence the importance of resistance and insulation.

Insulation is also made important by the fact that, if it is faulty, noises on the telephone will result.

Capacity attenuates the amplitude of the telephone speech currents. To avoid this, inductance may be added, but the addition of inductance also implies the addition of impedance, so that only a certain amount is allowable.

There is a sixth factor, which the lay mind would probably hold to be of first importance, namely cost.

Copper *must* be used for telephone wires, and because of this, if for no other reason, heavy wires cannot be used in order to reduce the resistance.

Some of the difficulties which have always confronted telephone engineers having been indicated, it is of interest to consider how they have been overcome. The problems of increasing the range and reducing the cost of the telephone have been studied for over 40 years. Improvements have, up to the present time, been made in six stages. The original Bell telephone was limited in its range of operation by the small amount of current generated by the transmitter. The first developments were the introduction of the microphonic transmitter and improvements in the receivers. Then, in the late 'eighties, hard drawn copper wire came to be used, and our chief cities and London and Paris were soon linked up by telephone. Telephone engineers first sought to eliminate transmission losses and to make their lines efficient.

Ten years' experience brought them to the third stage, viz. the introduction of "loading," i.e. the insertion of inductance into the telephone circuit. Loading may be of two kinds, (1) coil loading, and (2) continuous loading. Coil loading is the introduction into the circuit of coils of wire wound, as shown in Fig. 1, upon a soft-iron core. These coils are introduced at carefully calculated intervals on long lines, their number and spacing depending on the nature and length of the circuit. Continuous loading is effected by the winding

of soft iron wire or strip over the copper conductor before annealing.

Annealing coats the iron with a light film of oxide, and so to some extent insulates it from the wire. Continuous loading is not quite as efficient as coil loading, but both are important.

Loading made speech practicable over three or more times the distances previously possible. In 1913 the fourth stage of development was reached, when cable balancing, which will be referred to later, was introduced. Quickly following it came the introduction of the thermionic valve incorporated in the telephone repeater, and, concurrently, came the discovery of "phantom circuits" which, it has been found, may be coil-loaded and fitted with telephone repeaters. When two separate circuits are used, each as a conductor, a phantom circuit is produced. The first two circuits are known as "physical" circuits. Thus, four physical circuits give rise to a total of seven circuits, three phantom circuits being possible, since two may be utilized to produce a third.

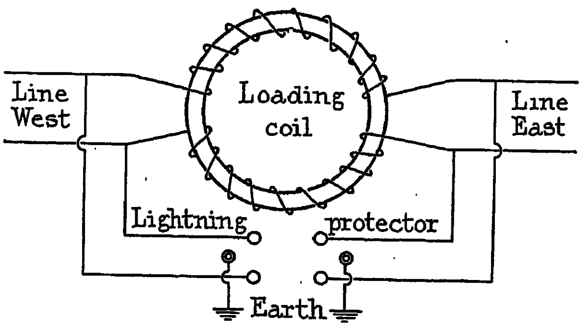


FIG. 1.—Coil loading.

At the present moment phantom circuits, repeaters and cable balancing are being rapidly developed, and experiments are being made with "wired wireless." Two comparisons will serve to indicate the progress that has been made. Our first long-distance telephones worked over distances of 100 to 200 miles. To-day it is possible to telephone to San Francisco from New York, a distance of 3 400 miles. Loading and repeaters have made this distance equivalent to 60 miles of standard cable.* The original telephone wires weighed 800 lb. per mile. The New York-Chicago cable is an aerial cable weighing 9 lb. per foot, and is 2⅝ inches in diameter.

It is supposed to contain 206 pairs of conductors, the weight of which does not exceed 40 lb. per mile, and may be as low as 20 lb. It follows a circuitous route of over 800 miles.

TELEPHONIC REPEATERS.

Having sketched the development of long-distance telephony, the author will now refer in some detail to telephonic repeaters. A telephonic repeater is an apparatus consisting of transformers, batteries and a thermionic valve, and is used for amplifying and re-transmitting currents along telephone lines. It has three great advantages: (1) It makes telephony possible over long distances; (2) it enables smaller gauge wire to be used for speech currents; and (3) it makes the use of underground cables possible for long-distance telephony.

It is obvious that no mechanical relay can possibly be used in a telephone circuit, since it would involve a time-lag. The relayed current must have the same form as that produced by the transmitter. Therefore the only types of relay possible are those in which speech currents are used to modify a magnetic or electric field. Magnetic control has twice been tried, but has not been developed commercially.

Electric control has proved more successful. The simplest example is the Cooper-Hewitt circuit, in which a mercury-vapour discharge tube is used in series with a high-tension battery and transformer secondary. The speech currents flow through the transformer primary and set up a large increase in the tube circuit, which is used to operate the receiver.

The thermionic valve invented by Dr. J. A. Fleming has, however, superseded all other forms of relay. If a body be heated to or above a temperature of 1 500° C. the force of cohesion between its electrons is overcome and some are emitted. If it be enclosed in a lightly exhausted globe, and if a positively charged plate be also enclosed in the globe at a little distance from the hot body there will be a flow of electrons to the positively charged body. If the difference of potential between the two be maintained at a sufficiently high value, the electrons will acquire so high a velocity that they will split up into positive and negative ions any molecules of gas with which they may come into contact. The latter will increase the flow of current between the hot body and the plate, but the positive ions will disintegrate the hot body by their bombardment. Since the hot body is usually a filament, the disintegration shortens the life of the valve considerably. The valve is rendered unstable also by the absorption of the residual gas molecules by (probably) the glass, and the vacuum is thus increased.

It is obvious, therefore, that soft valves cannot be made or maintained identical in any quantity. By reason of their greater stability and longer life, hard valves have come to be used most widely in repeaters. These have a vacuum of 10^{-8} mm of mercury, and, by suitably treating the parts, can be made very stable since occlusion is prevented and ionization is impossible. They are capable of a greater power output than soft valves, and are independent of the external temperature. The modern valve contains three electrodes, the third, known as the "grid," being perforated and placed between and insulated from the filament and plate. If a negative charge be placed on this grid it will repel the electron flow and prevent it reaching the plate. If it be positively charged it will assist the flow to the plate. Varying charges on the grid will clearly result in varying filament-plate currents. The speech currents in the telephone circuits are transformed up and used to vary the grid potential.

* Standard cable is a dry-core paper-insulated lead-covered cable, the wires of which have a loop resistance of 88 ohms per mile, an average mutual capacity (wire-to-wire) of 0·054 μF per mile, and an average insulation resistance of not less than 200 megohms per mile between wires.

Two equations may be given here. The first is due to Professor O. W. Richardson and is

$$N = aT^{-\frac{1}{2}}e^{-b/T}$$

where N = number of electrons emitted per square centimetre of hot body per second;
a and b are constants; and
T = absolute temperature of the body.

The second is due to Dr. Langmuir and is

$$I = A(V + Bv)^{3/2}$$

where V = voltage of plate, due to the high-tension battery;
v = voltage of grid, due to the grid battery; and
A and B are constants depending on the construction of the valve.

Leiben-Reisz relay.—This relay has two unique features. The anode and cathode are 4 inches apart instead of the usual $\frac{1}{4}$ inch or $\frac{1}{2}$ inch. A small quantity of mercury amalgam is enclosed in the coolest part of the tube and is used: (*a*) to reduce the resistance of the discharge path by mercury vapour; (*b*) to maintain constant pressure; and (*c*) to carry the electrons and avoid occlusion. The valve is used in a circuit similar to that employed for the present-day hard valve, with the exception that the high-tension circuit has a resistance in it which limits the discharge.

Round valve.—Two important properties of this valve are: (1) The plate surrounds the grid, which again surrounds the filament, and in this way the electrification of the glass is said to be prevented; and (2) a small piece of asbestos surrounded by a heater coil is used to soften the vacuum when required.

TABLE 1.

Type of Valve	Magnification	Speech Tests: Improvement, One direction	Speech Tests: Improvement, Duplex	Speech Tests: Articulation	Stability	Lag	Life, in hours
		m.s.c.	m.s.c.				
Audion	Output does not bear a definite relation to input	8 (with 1 valve) 25 (with 2 valves) 30 (with 3 valves)	10	Good	Very stable	Nil	1 000 (given by makers)
Leiben-Reisz ..	Test not made as valve unstable	—	22	Good when valve adjusted	Very unstable	15 mins.	1 000 (given by makers)
Round	Good	28	22	Good	Very stable	3 secs., (increasing with age)	Upwards of 600
Post Office low vacuum	Large	25 to 30	—	Good	Good	Nil	200 to 500
P.O. hard	Greater than with soft valves	—	25	Very clear	Extremely stable	Nil	Not tested longer than soft

It is clear from this second equation that if v is maintained negative by the grid battery, small changes in current value transformed up will cause large changes in the value of v, and hence of I, the plate current.

SOFT VALVES AND TELEPHONIC REPEATERS.

Four types of soft valves have been applied to telephonic repeaters and tested by the Post Office, namely, the audion, Leiben-Reisz, Round and Post Office low-vacuum valves.

Audion.—This consists of a three-stage resistance amplifier. The speech currents are stepped up by a 25 : 1 transformer and are used to vary the potential of the first of three valves in cascade. The high-tension battery supplies 50 volts and the high-tension current is used to operate the receivers through a 4 : 1 step-down transformer.

Post Office low-vacuum valve.—This is similar to the Round valve, but is larger, with a view to obtaining greater magnification with ordinary speech currents.

POST OFFICE TESTS ON VALVES.

The valves have been subjected to five classes of tests.

(1) *Magnification.*—This is the ratio of "Output of the relay, in micro-watts" to "Input to the relay, in micro-watts." To test the magnification an alternator is used to supply current at speech frequency, and a non-reactive resistance absorbs the amplified current. The results are expressed graphically.

(2) *Speech tests.*—These are made on from 30 to 50 miles of standard cable. The transmission efficiency is compared with a direct circuit, (*a*) with, and (*b*) without, the repeater working. The difference between (*a*) and

(*b*) gives the improvement due to the relay, expressed in miles of standard cable. The improvement is measured with the repeater working (*c*) in one direction, and (*d*) in both directions.

(3) *and* (4) *Stability and life tests.*—The repeater is run continuously until the valves burn out or until the efficiency falls below a certain value.

Periodical tests are made to ascertain the efficiency and the stability of adjustments.

Table 1 gives the results of Post Office tests.*

Lag tests are made to determine the time required to reach full efficiency after the filament battery has been switched on. This time should be very short so that (1) the filament is lighted only while speech is taking place, and (2) the life of the valve shall not be shortened by useless burning.

(5) *The d.c. characteristic* is determined and recorded as a graph. To obtain the points for this graph the currents across the input secondary and output primary are measured by means of a reflecting galvanometer for varying grid potentials brought about by a potentiometer. The galvanometer records on a sensitized paper attached to the potentiometer sliding contact.

Results of tests made with a hard valve in 1917 are given in the table, together with those made with soft valves.

Hard Valves in Telephone Repeaters.

The Post Office is at the present time using hard "French" valves almost exclusively in its repeaters. Two forms are being tried—the B.T.H. valve and a valve in which the grid and plate are both spirals of wire (enabling them to be thoroughly heated during manufacture to expel occluded gas). The advantages of hard valves have already been enumerated. There are two disadvantages which, however, do not outweigh the advantages. They are: (1) The high vacuum gives the filament-grid circuit a very high resistance and so makes the design of the input transformer difficult; and (2) the amplified current being greater than that with soft valves there is greater liability to cross-talk.

Types of Repeater Circuits.

There are two types of repeater circuit—the single relay and the double relay. Both are modifications of the Edison repeater system, in which the speech currents pass through the primary of a transformer and induce currents in the secondary and relay circuits. The microphone is actuated and produces strengthening currents in the secondary of its induction coil. These currents are led to the centre of the transformer primary and, if the impedances of the lines on the two sides are equal, they do not affect the receiving coil.

The single-relay repeater.—The way in which the Edison system has been modified for use with a valve is shown in Fig. 2.* It is important to notice that this system requires two conditions, (1) the division of the amplified current at the centre of A, and (2) lines electrically equal on each side of A. These conditions are great drawbacks in a single-repeater circuit. Thus, if more than one repeater be used in a circuit, unless the transmission losses between the repeaters absorb the amplified current which is "reflected back" from each repeater there will be an "echo" effect and repeaters will re-amplify and re-transmit the currents already amplified in the repeater ahead on the line, thus making speech impossible. Again, if only one repeater be used, condition (2) requires that either (*a*) the repeater shall be at the electrical centre of the telephone line, or (*b*) an accurate artificial balance shall be arrived at for the lines on each side of A. These requirements are very difficult to obtain in practice, but unless they are obtained the valve circuits will oscillate, and the valve will "howl" and drown all speech. Consequently the single-relay repeater is very little used, being confined to underground cable circuits, since aerial circuits cannot be balanced.

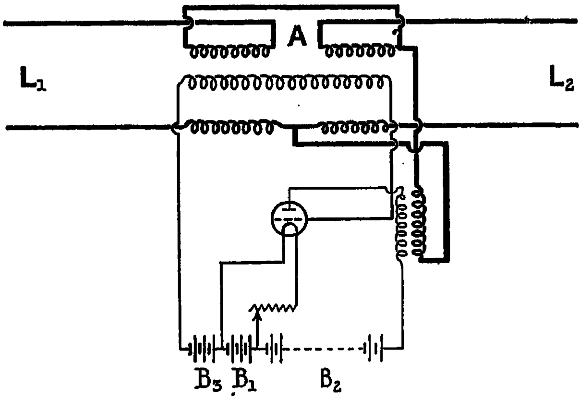


FIG. 2.—Single-relay repeater (1916).

A modification of the single-relay repeater is worthy of consideration, but the author is not aware that it has yet been tested commercially. It has been developed by Herr van Kesteren, a Dutch telegraph engineer. His scheme of connections is shown in Fig. 3. Imagine the speaker to be at X′ and the person spoken to at Y′. X′ is connected to X and Y′ to Y either (*a*) through a direct, single pair of wires, or (*b*) through a transformer. Speech currents arriving at X divide, one portion passing through the amplifier A and on to Y and the other being stopped by the amplifier B. The first current will continue beyond Y and tend to return to X, so that it is essential, in order to avoid "echo" or "reflection," that the circuit shall be sufficiently long, to enable any excess current to be absorbed by the transmission losses. So long as this is the case the circuits are stable and, as no balancing is required, the repeaters can be made highly efficient. With such a four-wire circuit the weight of trunk lines in the British Isles might be reduced to 20 lb. per mile, if loaded and supplied with repeaters at intervals of 50 miles. Theoretically there is no limit to the distances over which speech may be made possible by the van

* In this table all the values under the heading "Life" are only approximate. The life given by the makers is probably only a rough value, and the author has no information as to how they make their tests. They make no statement as to the rate of change of efficiency during life tests, so that some part of that life may be of no practical value. The Round valve was not given a fair test as to its life, and the Post Office low-vacuum valve was run at a high rate while under test and would probably show a higher value under fairer conditions.

Kesteren system. Experiment has shown that it will reduce a circuit 90 m.s.c. in length to 15 m.s.c. (further reduction would result in "echo"). Speech over a distance equivalent to 15 m.s.c. is loud. Now, New York to San Francisco is a distance equivalent to not more than 60 m.s.c. without repeaters (the actual distance is 3 400 miles). This shows that loud speech over a distance of, say, 5 000 miles is a practical proposition and, since the four wires necessary may be comparatively thin, cost is not a prohibitive factor. There are practical difficulties, however, which make it doubtful if the widespread introduction of a four-wire trunk system is practicable at the present time, although there is a wide range of application open to it. The system has the disadvantage that, unless a four-wire junction is available, when two van Kesteren circuits are to be joined together, the total impedance will make them equal to the sum of their standard cable equivalents. In the case of the balanced system with double-relay repeater (to be described later) this is not so.

Whether the van Kesteren system will ever be used commercially on a large scale is a matter of opinion. The author gathers that British Post Office electrical engineers are more in favour of the development of more perfect balance in the double-relay repeater. This relay has the great advantage that it can be introduced into the existing metallic circuit system without requiring the erection of new lines.

The double-relay repeater.—A diagram of a double-relay repeater is given in Fig. 4. It will be seen that it consists essentially of two single-relay repeaters with the addition of two artificial balancing circuits. The incoming speech current is amplified by one valve and passed on to the outgoing circuit through a transformer in the plate-filament circuit. As in the single-repeater circuit, the current divides in the line transformer of the second relay and passes partly through the line balance and partly along the line. The "up" and "down" circuits are separated by the repeater and, if the artificial balances are made and maintained accurately, "howling" will be impossible. Due to this arrangement it is probable, however, that there will be different efficiencies in different directions. The artificial balances referred to are combinations of resistance, capacity and impedance arranged to reproduce exactly the electrical conditions and qualities of the lines to which they are connected. They are designed from the results of experiments and calculations made at the repeater stations. The method of calculation is given in Professor A. E. Kennelly's book on "The Application of Hyperbolic Functions to Electrical Engineering Problems."

The efficiency of the double-relay repeaters depends largely upon the design of the transformers, the ratio of transformation of which depends upon the impedance of the line and the apparent resistance of the valve.

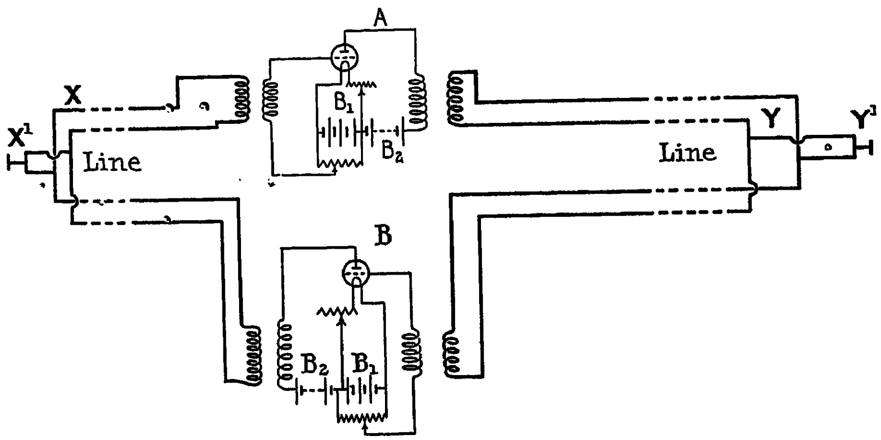


FIG. 3.—Van Kesteren's system.

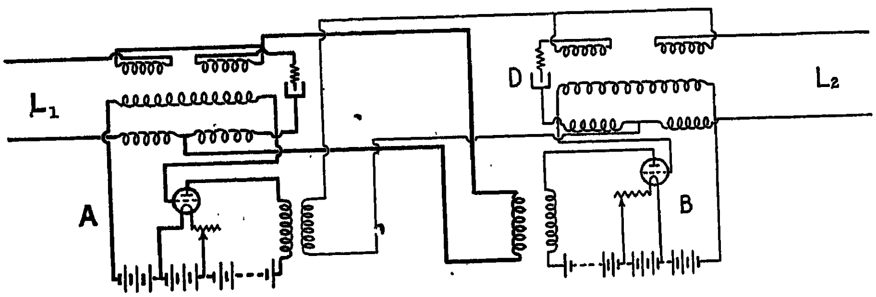


FIG. 4.—Double-relay repeater.

Since this resistance is very high the number of turns in the transformer secondary is also very high for maximum efficiency, but too great a number leads to a reduction in the clearness of articulation owing to capacity effects in the windings. Attention has already been drawn to this disadvantage. The double relays also suffer from the disadvantages of multiplicity of apparatus, and it is not possible to signal through them by means of a magneto without supplying additional relays. However, the Post Office hopes to evolve a system of signalling in which a current of such frequency will be employed that the repeater will transmit signals as it does speech currents. Such a system would minimize both delays and the quantity of apparatus necessary.

Some few figures in connection with the present-day repeater may be of interest. The ratio of the input (step-up) transformer is 40 : 1, and that of the output (step-down) transformer 10 : 1. The heating battery is an 8-volt accumulator supplying 0·9 ampere per valve. The high-tension battery is of 200 volts with an electron flow of 1·5 mA per valve. This battery, similarly to the 5-volt grid battery, may be of dry cells or small accumulators.

Results.—The improvement effected by repeaters depends upon the electrical length of the line. A long line, i.e. one equivalent to more than 15 m.s.c., has a lighter load than a short one and correspondingly greater sensitiveness. In this case the improvement may be equivalent to from 25 to 32 m.s.c. Short lines with their heavier loads and lack of balance (implying lack of sensitiveness in the repeater) give an improvement of from 12 to 17 m.s.c.

It has been calculated that if repeaters could be inserted at intervals of 15 m.s.c., and the lines could be satisfactorily adjusted, an improvement of from 15 to 20 m.s.c. would be brought about.

The New York–Chicago and the New York–San Francisco telephone lines have already been referred to.

Cost.

The question of cost is an important one. It has been estimated that a repeater costs £50 a year to maintain. This is a higher figure than for loading but the improvements are far greater. The first cost is negligible by comparison with the savings effected in line costs. The heaviest item is due to attendance, but a second estimate is to the effect that two attendants could easily look after 100 repeater circuits, so that this item should not be very heavy. On the other hand, it may be possible to save £15 000 annually by the introduction of repeaters into main trunk lines radiating from London. As old telephone lines become obsolete and are replaced, the advantages of the use of repeaters should become apparent in Post Office estimates.

Conclusion.

Post Office engineers have anticipated the day when all trunk lines will be run with a standard gauge conductor, which will not be heavier than 50 lb. to the mile and will have an insulation resistance of 10 000 megohms per mile. A little later they hope to have one standard conductor for all subscribers and local junction circuits. They believe that it will be possible to telephone from any one point to any other in the United Kingdom and, further, that transcontinental and transoceanic telephony will soon be a reality. Already international telephony is a reality to some extent, but in the near future it is hoped to link up the trunk systems with the transcontinental and transoceanic cables. France, Italy, Japan, America and Germany are all using and experimenting with telephonic repeaters and have been so doing for some time, but the author has been informed that the British Post Office leads the field. The Post Office is greatly handicapped by a lack of sufficient research staff. The present staff is inadequate for the work that needs to be done, and the author believes that the Post Office is trying to extend the Research Department and that it intends to get into touch with our Universities in an endeavour to secure more men of the right sort who will keep us ahead in the struggle for efficiency and economy.

The author would like to express his indebtedness to Mr. J. Richardson, the Executive Engineer of the Birmingham Post Office, for much valuable information and advice and for permission to inspect the Birmingham repeater office. Lastly, he would like to thank Mr. E. T. G. Donovan, the Chairman of the Students' Section of the South Midland Centre, for his suggestion that a paper should be written on the subject of telephonic repeaters.

APPENDIX.

In the preparation of the paper the author has consulted the following publications:

J. G. Hill: "The Loading of Aerial Lines, and their Electrical Constants," *Institution of Post Office Electrical Engineers, Professional Papers*, No. 54.

——: "The Loading of Underground Telephone Cables for Phantom Working," *ibid.*, No. 68.

A. B. Hart: "Telephonic Repeaters," *ibid.*, No. 75.

C. Robinson, B.A., and R. M. Chamney, B.Sc.: "Gas-discharge Telephone Relays, and their application to Commercial Circuits," and "Technical Developments of Telephonic Repeaters since 1917," *ibid.*, No. 76.

All the diagrams in the present paper were reproduced from these papers.

AUTOMATIC AND SEMI-AUTOMATIC RAILWAY SIGNALLING.

By H. S. Petch, B.Sc., Student.

(Abstract of paper read before the London Students' Section, 2nd December, 1921.)

Summary.

The evolution of railway signalling to meet the demands of safety, and later of traffic capacity, has culminated in the modern automatic and semi-automatic systems, which are designed to overcome the defects of manual working. In addition they offer valuable advantages, as their use permits of increased speeds and augmented services, which increase the full-load capacity of a given line; while their flexibility allows of a ready adjustment of traffic control to traffic variations.

An early system using train-controlled switches is briefly touched upon, and its weak points are noted.

The track circuit, which forms the basis of all modern automatic signalling, is considered in its simplest form, and also as modified to suit electrified lines.

Apparatus controlled by track circuits is described, together with additional schemes for its safe operation.

The functions and chief features of semi-automatic working are dealt with, and the advantages peculiar thereto are pointed out.

Finally, a description is given of some auxiliary apparatus designed to expedite the handling of traffic.

Introduction.

The organized control of railway traffic came considerably later than the introduction of railways, and was first carried out solely on a time basis. Signals had no definite place in the regulation scheme, and were originally used for such purposes as stopping trains to pick up passengers. It was not until the danger of the time-spacing of trains was realized, and the block- or distance-spacing system was adopted, that signals achieved their present-day position as controllers of train movements.

At first scattered about as convenience or fancy dictated, the operating levers were finally centralized, and this, with the introduction of interlocking, formed the genesis of the signal box.

In 1889 the Board of Trade enforced the block-spacing system on all passenger lines, and so practically completed the development from the standpoint of safety. From that time onward the progress which has taken place has been towards a signalling system which, by its reliability and speed of operation, should allow of maximum traffic capacity. This has been accentuated by electrification, the full possibilities of which cannot be realized with the manual block system.

Advantages of Automatic Signalling.

It is irrefutable that the manual block system, with its block indicators and complex bell signals, is entirely dependent for its safety on the human element and implicit obedience to rules. This may be quite satisfactory provided the density of traffic is not great, but it inevitably results in severe mental strain and consequent risks if the traffic density be at all high. Such achievements as 50 trains per hour are unattainable. The lock-and-block system, which relieves the signalman of a great deal of responsibility, is an advance, as trains are rendered in a large measure self-protecting; but full automatic working, which is the logical outcome of the lock-and-block system, appears to possess the following advantages over its prototype:—

(a) The elimination of the human element removes all danger of fatigue, renders the service less dependent on labour conditions and, by a psychological effect on the drivers, conduces to consistent high speeds.

(b) Speed may be maintained on the necessarily short sections found on city lines, the delays occasioned by telegraphing acceptance of trains being avoided.

(c) The flexibility of automatic working allows of an easy adjustment of the signalling system to deal with changes in traffic density. A few changes in wiring will achieve a result in an automatic system that would have necessitated, in a manual system, a new signal cabin and much fresh equipment.

Lay-out of Signalling.

In a manual system a section is always treated as blocked unless specifically marked "clear" by the responsible signalman. The normal position of a manually operated signal is therefore at danger. An automatic signal is simply an indicator of the state of the section it controls, and its normal position is in consequence the "clear" position. It will be apparent that, with automatic working, trains may follow each other at an interval limited only by the time taken to traverse the longest section on the route, due regard being paid to time lost at junctions and in stations. The best lay-out of sections is therefore that in which trains traverse each section in equal times, and, as a change in load (i.e. passengers to be carried) will affect the time spent in station sections, it is obviously an advantage to be able easily to modify the signalling lay-out.

Bar-and-treadle System.

The automatic system which perhaps follows most closely on the lines of manual working is the "bar-and-treadle" system. This system is now obsolete, but it deserves a brief description.

The equipment for each block section comprises a bar and a treadle, which are switches opened and closed respectively by the passage of a train over them; a relay; a source of electromotive force; and, of course, a signal. The power circuit of the signal is

closed when the relay is operated, and the signal is thus held in the "clear" position.

When a section is clear, a circuit is closed from the battery, through the bar, a front contact of the relay (i.e. a contact closed when the relay is operated), and the relay coils. The relay is thus locked when operated, and the signal indicates "clear."

The entrance of a train into the section opens the bar, which is placed some 120 feet ahead of the signal, and the relay releases, as its holding circuit is broken. The signal power circuit is broken by the release of the relay, and, as the holding circuit of the latter is now open at the relay front contact, the closing of the bar after the train's passage does not again operate the relay. The signal therefore goes to "danger," and remains in that position while the section is occupied.

The train passes on, and in due course releases the signal of the next section at the next bar. Some 20 feet beyond the bar of the next section is the treadle of the first section. This is closed as soon as the train reaches it, and an operating circuit for the relay of the first section is then completed via the battery, the treadle, the bar of the next section at normal, the signal of the next section in the danger position, and the relay coils. The relay operates, and the front contact again completes the holding circuit, so that the signal of the first section is again held clear. The operating circuit of the relay is taken through the next signal so that the first section shall not be shown "clear" if the next signal has failed to go to "danger."

It is clearly important that only the passage of a train shall close the treadle. For this reason, treadles are usually operated by rail deflection, mercury often being employed to multiply the movement.

The bar-and-treadle system has the serious defect that the rear part of a train which has divided due to a broken coupling is not protected, as the front part will operate the treadle on leaving the section, so putting the controlling signal to "clear."

The Track Circuit.

The track circuit, which is the basis of all modern automatic signalling, had an early origin, but was not brought into general use until recent times. It is called upon to function faultlessly under very severe conditions, and does so remarkably well. The fundamental principle involved is the continuous protection of an occupied section, as distinct from the "load and fire" action of the bar-and-treadle and kindred systems.

Fig. 1 shows the simplest possible direct-current track circuit. One of the running rails is bonded continuously along the line, while the other is divided by special insulated fish-plates into sections corresponding to the signal sections. The sectioned rail is also bonded between the section points. At the "exit" end of the section a source of electromotive force is connected across the rails through a fairly high resistance. At the "entrance" end a relay is bridged across the rails, and this relay controls the signal protecting the section. Any conductor of sufficiently low resistance will shunt the relay and release it if it is also bridged across the rails. There is a permanent shunt across the relay caused by the leakage path over sleepers and ballast, and the resistance of this leakage path varies from time to time from megohms to a few ohms, depending chiefly upon weather conditions.

Now, any given relay has definite operating and holding currents, and definite voltages must therefore be maintained at its terminals to operate it and to prevent it releasing. It will be apparent from Fig. 1 that, in a given set of conditions, there will be a certain value of the ballast leakage resistance which will prevent the relay operating with a clear track. This may be called the "ballast failing resistance", and, clearly, the particular value which will produce failure in a given case is controlled by the value of the series resistance. The particular ballast failing point for which the series resistance is set is a matter of great importance. It must not be made higher than the normal resistance of the ballast leakage path, or continual failures would result in damp weather. On the other hand, it must

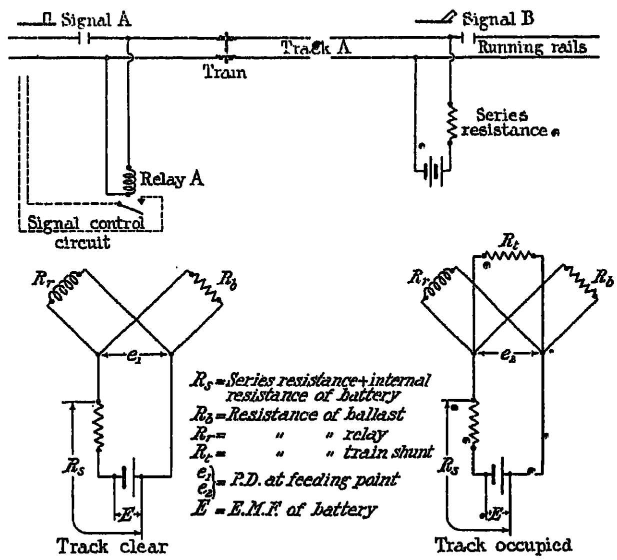


FIG. 1.—Simple d.c. track circuit.

be kept as high as possible, as upon it depends the capability of the track circuit to deal with train shunts of high resistance. A remedy for track circuits which, by reason of their excessive length or damp situation, necessitate the adoption of an unreasonably low ballast failing point, consists in splitting the section into several track circuits each of which exerts control on the signal.

The resistance of the shunt introduced by the presence of a train in a section must so reduce the combined resistance in series with the feeding resistance that the potential difference across the rails falls below that necessary to hold the relay in operation. For a given track there is thus a maximum effective train shunt resistance, and this will clearly have its smallest value when the ballast leakage resistance is infinite. It is important that a track circuit shall have the highest possible effective train shunt resistance, as train shunts, in common with ballast leakage, are very variable, being affected by the weight of the trains and the state of the contact between wheels and rails.

The connection between the ballast failing point

and the maximum effective train shunt can be shown mathematically.

Let E = E.M.F. of battery,
e = potential difference at the feeding point,
e_o = operating voltage of relay,
e_h = holding voltage of relay,
e_m = maximum potential difference across rails,
k = ratio e_o/e_h.
R_s = series resistance (including battery),
R_r = resistance of relay,
R_b = resistance of ballast leakage path,
R_t = resistance of train shunt,
$R_{b'}$ = ballast failing resistance,
$R_{t'}$ = maximum effective train shunt.

(*Note.*—Rail resistance is negligible if the bonding is well carried out.).

A general expression for e is:—

$$e = \frac{E}{1 + R_s[(1/R_r) + (1/R_b) + (1/R_t)]} \quad . \quad (1)$$

The value of R_s must satisfy the following equation:—

$$e_o = \frac{E}{1 + R_s[(1/R_r) + (1/R_{b'})]} \quad . \quad . \quad . \quad (2)$$

whence
$$R_s = \frac{E - e_o}{e_o[(1/R_r) + (1/R_{b'})]} \quad . \quad . \quad . \quad (3)$$

From Equation (1) it will be apparent that the maximum rail potential e_m will occur when R_b and R_t are both infinite, and will then be:—

$$e_m = \frac{E}{1 + R_s(1/R_r)} \quad . \quad . \quad . \quad . \quad (4)$$

$$= \frac{ER_r}{R_r + R_s} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Now, the maximum effective train shunt $R_{t'}$ will be that resistance which will reduce the track potential from its maximum value e_m to the holding P.D. of the relay, e_h, and so just release the relay. This can be shown to be given by the equation

$$R_{t'} = \frac{R_s}{E[(1/e_h) - (1/e_m)]} \quad . \quad . \quad . \quad (6)$$

For a given relay, the ratio $e_o/e_h(= k)$ is fixed, and substituting k for this in Equation (6), together with the previously found values for e_o, e_m and R_s, the final expression for $R_{t'}$ is:—

$$R_{t'} = \frac{(kE - e_h)R_rR_{b'}}{(1 - k)ER_{b'} + R_r(E - e_h)} \quad . \quad . \quad (7)$$

Since E, e_h and R_r will have fixed values for a given track circuit, it is clear that $R_{t'}$ will be equal to $R_{b'}$ when k is unity (i.e. when the operating and holding voltages of the relay are identical), and that it will be less than $R_{b'}$ for all values of k below unity. Thus under the worst conditions the maximum effective train shunt will be somewhat less than the ballast failing resistance. This demonstrates the importance of adjusting a track to the highest possible ballast failing point, and also the desirability of using a relay the operating and holding currents of which are as nearly equal as possible.

Direct-current Track Circuits for Electric Railways.

While the simple track circuit is quite suitable for use on steam railways, the proximity of the conductor rails on electric lines introduces the probability of considerable leakage currents from the traction power circuits. Such leakage currents could easily produce a dangerous failure on a simple track circuit, and therefore special circuits have been devised to meet this difficulty. One such scheme, the invention of Mr. H. G. Brown, employs a pair of polarized relays, one at either end of the track circuit, and both of these must be operated before the protecting signal can go "clear." The relays are operated by current in the proper direction only, and any fault or leakage current which may cause one to operate will flow in the opposite direction in the other and so prevent its operation. To secure economy of power, the polarizing coils of these relays are closed by a pilot armature which is attracted only when sufficient current flows in the main coils, which are bridged across the rails as before.

The Alternating-current Track Circuit.

This is now generally conceded to be the most economical and reliable form of track circuit for electric railways. The following are some of the advantages which it possesses:—

(*a*) Alternating-current apparatus is unaffected—except by magnetic saturation and overheating—by direct-current leakage currents.
(*b*) Economy in wiring is obtained, due to the ease of transformation to the low voltages necessary for track circuits.
(*c*) A given track circuit will have a higher maximum effective train shunt as, in addition to the utilization of current-changes, an alternating-current circuit also employs changes of phase angle.

Alternating-current track circuits are fed at the exit end from the low-voltage secondaries of the feeding transformers through regulating resistances. These transformers, which are individual to the tracks, are fed from main transformers, the primaries of which are connected to the signal mains. The relays used are usually of the two-winding type. The field windings are continuously excited, and the armature windings bridge the rails. The relays are ironless, to minimize power consumption, and function as dynamometers. An induction-type relay is sometimes used, but its working force is smaller than for the two-winding type.

Fig. 2 shows a typical a.c. track circuit scheme embodying the above features and utilizing impedance bonding, which allows of the use of the running rails as regular returns for traction current, at the same time preserving the independence of the track circuits.

A theoretical discussion of the a.c. track circuit is beyond the scope of this paper, but in 1920 a comprehensive paper on the subject appeared in the *Journal*.*

Control of Apparatus by Track Circuits.

Both electric and pneumatic drive are used for signals and points, but on an electric line the flexibility of the electric drive makes it by far the more suitable. In the all-electric system, the circuits controlling the various pieces of apparatus are usually made and broken directly by the track-circuit relays. In the electro-pneumatic system the track relays control solenoid-operated valves, which in turn control the admission and release of compressed air to the operating cylinders of the apparatus concerned. In both systems the control circuits are usually fed from the same mains that feed the track circuits.

Signals and "Signal-on" Protection.

The simplest signals are those used in tunnels, and of these there are two general types. The first employs separate lamps and lenses for the red and green indications. The other uses one lamp only with an interposed spectacle frame, which puts a green glass in front of the lamp when raised by a solenoid, and a red glass when the de-energized solenoid allows the spectacle to fall.

In the two-lamp type the lamps are in a separate ventilated chamber, and are controlled by a relay enclosed in the signal. The red-lamp circuit is a local one, to reduce to a minimum the chances of its failure. The green lamp and the signal relay coils are energized through track relay contacts so that the green lamp will be extinguished by the release of the track relay in the event of the signal relay sticking up. The signal relay carries contacts to control repeater signals, and also the signal-on contacts.

The object of "signal-on" protection is to prevent the marking "clear" of a section if for any reason the signal of the section ahead has failed to go to "danger" behind a train. In Fig. 2 it will be seen that the circuit of the feeding transformer of section B passes through the back contacts of signal C(S_c) and front contacts of relay C(R_c) in parallel. Thus, assuming a train to have entered section C and to have released R_c, and that for some reason S_c fails to release, the feed to track B will be broken. Consequently, although track B may be unoccupied, R_b is prevented from operating and putting S_b "clear" until the feed to track B is restored either by the release of S_c or by the subsequent operation of R_c when the train leaves section C. It will be seen that this is equivalent to controlling a signal from two track circuits in the event of the second track failing to release its own signal.

On lines which run in the open, semaphore signals are used. In the upper-quadrant pattern the arm is raised through 45° by a motor which drives through a magnetic clutch. Both motor and clutch are energized through the track relays, and, when the arm has been raised sufficiently, the motor is cut out, leaving the arm held "clear" by the clutch. On the release of the track relays the clutch circuit is broken, so that the arm falls to "danger" by gravity, the shock being taken up by an air-cushion.

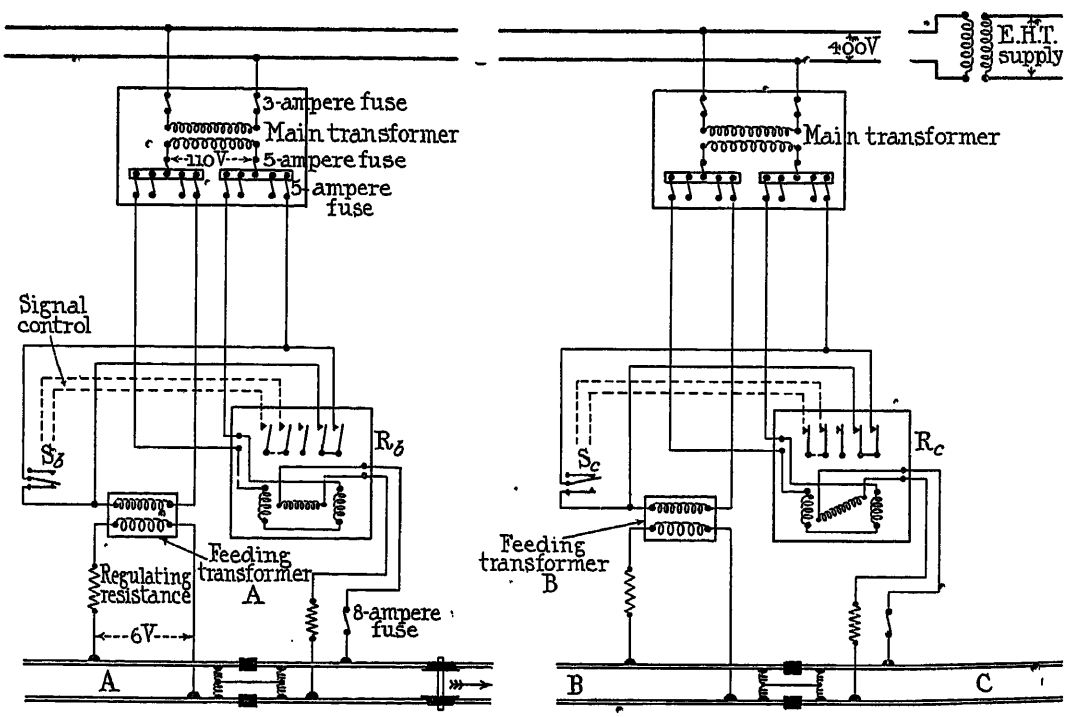


FIG. 2.—Alternating-current track circuit.

* *Journal I.E.E.*, 1920, vol. 58, p. 491.

Functions of Semi-automatic Signalling.

The systems of signalling so far dealt with have been suitable for sections having only one entrance and one exit. Sections involving choice of route, or where shunting operations take place, call for a certain amount of manual control. Semi-automatic signalling is designed to reduce this necessary manual control to a minimum, and so to retain the advantages of full automatic working as far as it is practicable. A signalman is necessary at a junction in order to switch trains to their correct routes, and also to decide as to priority when two trains converge toward the same road. By limiting his responsibility to these duties, and providing him with suitable apparatus, the traffic-handling capacity of a signalman can be increased to a very great extent.

Leading Features of Semi-automatic Systems.

(*a*) *Power control.*—The control of points and signals by power instead of by rods and wires reduces the signalman's work, and also renders the incorporation of special schemes of protection an easy matter. The levers in a power signal frame operate switch-drums, and are mechanically interlocked among themselves to prevent conflicting train movements. Thus, the lever of a signal which gives access to points cannot be pulled over unless the point lever concerned is in the correct position. Further, the pulling over of such a signal lever back-locks the point lever, to prevent the movement of the points during a train's passage. Again, the pulling of a point lever to set the road through a crossing prevents the pulling of the lever which would set the intersecting road. The switch-drums operated by the levers serve, of course, to control the circuits of the various points and signals.

(*b*) *Illuminated diagram.*—Above the lever frame in a semi-automatic signal cabin is mounted a diagram of the area of control. The diagram is set out on glass, and the various roads are frosted. The roads are divided to correspond to the track circuits, and each division is normally illuminated by a lamp behind the glass. The lamp circuits are controlled by line relays which serve to repeat the condition of the track circuit relays, and the fact that a particular track is clear or occupied is therefore shown on the diagram by the corresponding section being illuminated or darkened, respectively. Train movements are thus revealed in the cabin by the progress of dark sections along the otherwise illuminated tracks. In addition to the track circuit lamps, small red lamps are placed on the diagram in positions corresponding to the signals, and these are extinguished when the signals are "clear." As these lamps are controlled by the signal relays they serve as checks on the signal operation.

It is usual to indicate on the diagram one or two of the automatic track circuits on each line of approach to the junction, so that the signalman may have warning of oncoming trains.

The use of such an illuminated diagram allows the signalman to concentrate his whole attention on the lever frame, permits the placing of the signal cabin out of sight of the trains altogether; and prevents the working of the junction being interfered with by fog.

(*c*) *Control of points.*—In a power frame, a switch-drum which controls points has four positions. The point lever is capable of moving it to only one of the two inner positions, and in these positions, as shown in Fig. 3, the circuit of the point motor alone is completed. When power is thus applied to the motor, the bolt of the points is first withdrawn, then the blades are thrown over and, finally, the bolt is re-inserted. Power

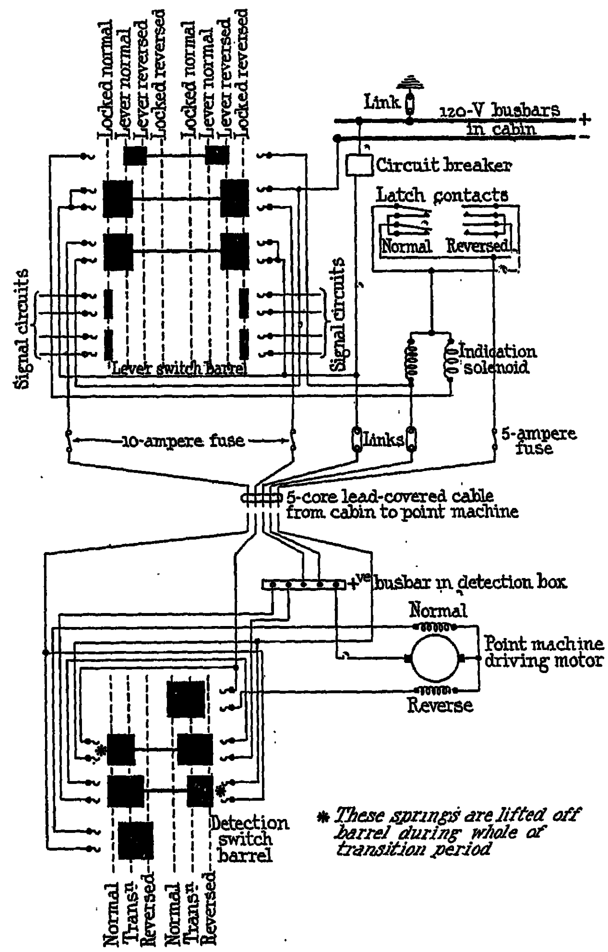


Fig. 3.—Circuit of power-operated points.

is cut off from the motor at the end of a stroke by a switch-barrel in the detection box, which switch-barrel is associated with, and controlled by, the bolt.

The detection switch-barrel is also responsible for the completion of the circuit of the indication solenoid which, when it operates, moves the lever switch-drum to one of its extreme positions. The contact fingers in the indication circuit are lifted clear of the detection switch-barrel by an auxiliary device if the point blades are not fully thrown, so that the fact that the lever switch-drum is in either extreme position is a guarantee that the points are safe for traffic.

It will be observed from Fig. 3 that the indication circuit is taken through contacts operated by the lever

latch, the lifting out of which opens the indication circuit, and so causes the lever switch-drum to leave its extreme position. It will also be noted that the indication solenoid has a low-resistance operating coil, and a high-resistance holding coil, the object of which is economy of power.

(*d*) *Control of signals.*—The signals used for semi-automatic working are identical with those previously described—but in this case they must normally stand at "danger." Signal lever switch-drums in a power frame are coupled direct to their levers, so that the points themselves must be safe for traffic before the signal circuit is closed. Finally, it will be seen that the control circuit of a signal passes through contacts on the line relays associated with the track circuits to which it gives access. Thus, a signal cannot be put to "clear" unless the section to which it admits is unoccupied, and, although put "clear" manually, a signal will go to "danger" automatically on the entrance of the train into the section.

In order to permit the passage of a train, the signalman will first set the road by the point levers, and immediately

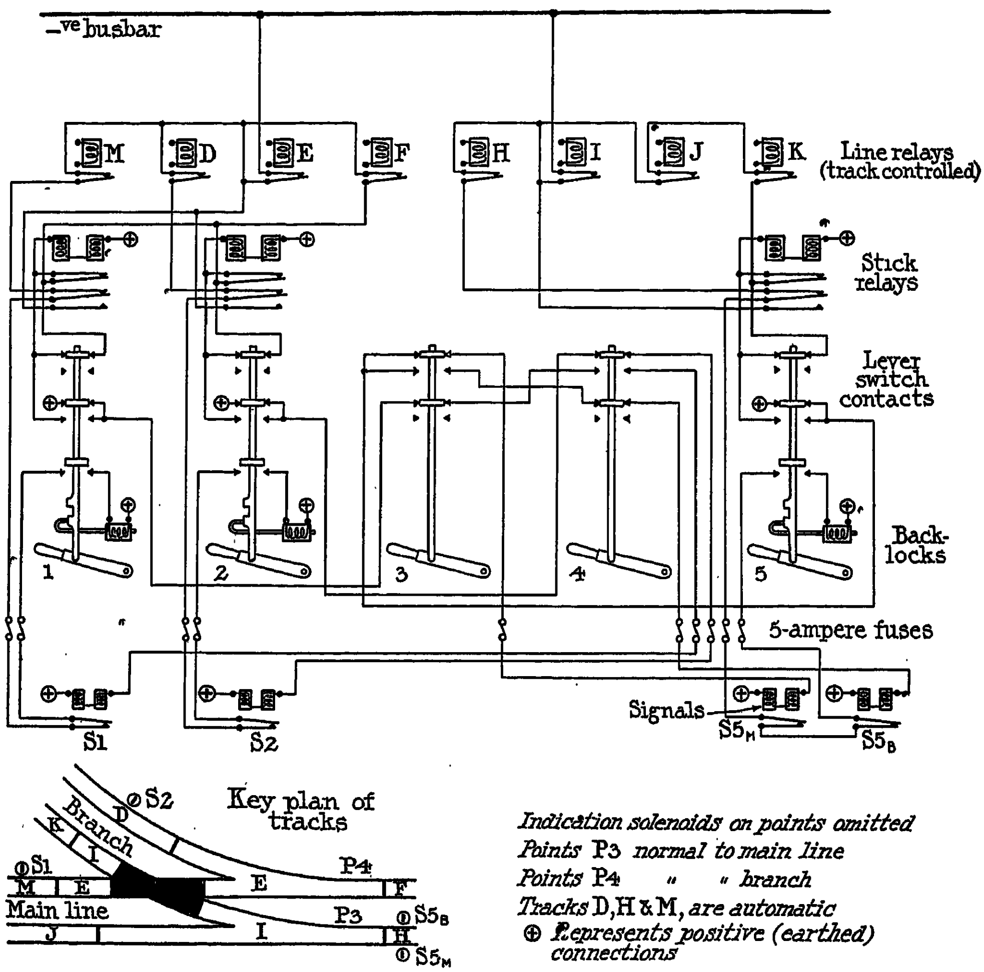


FIG. 4.—Signal circuits at a junction.

point levers, via the mechanical interlocking, prevent the closing of conflicting signal control circuits by locking the levers. Fig. 4 gives the signal control circuits of the junction shown on the diagram and shows that the control circuit of any particular signal passes through contacts on the switch-drums of any points to which the signal gives access. (For example, the circuit of signal S1 cannot be closed unless points P3 and P4 are normal and reversed, respectively.) As these contacts on the point lever drums are closed only in the extreme positions of the latter (see Fig. 3), it follows that not only must the point levers be thrown, but the throw the appropriate signal levers. The signals, however, will respond only when all the above conditions are fulfilled.

Fig. 4 also shows the ease with which one lever can be made to operate two signals. Thus, signals $S5_M$ and $S5_B$ are both controlled by lever 5, the selection being dependent on the position of the points P3.

(*e*) *Electric route-locking.*—It is essential for safety that once a train has been admitted to a section containing points it shall not be possible to disturb the setting of the road until the section is clear again. This is accomplished in a semi-automatic installation

by back-locking the signal levers electrically. Suppose, for example, a train to be approaching the junction in Fig. 4 along track M. The signalman will set the road for it by reversing points P4. He will then throw lever 1, which will mechanically lock and back-lock points P3 and P4, respectively, and put signal S1 to "clear" if the road is clear and the points are safe. As soon as lever 1 is thrown, however, the back-lock latch will drop into a slot in the switch-drum, and this will prevent the replacement of lever 1 and the consequent freeing of the mechanical locking of points P3 and P4, as the circuit of the back-lock release solenoid will be open at signal S1, and at line relay M, which will be released by the presence of the train in track M. The route for the train is thus guarded, and the train may proceed along it.

As soon as it enters track E, line relay E will release, thereby opening the circuit of signal S1 (which will go to "danger") and also releasing stick relay No. 1. The stick relay is so called because it has a locking action, and, when it is released, the back-lock release circuit of lever 1 will no longer be under the control of line relay M, so that the clearing of track M when the train leaves it will not free the back-lock.

The train may thus traverse the junction track E in perfect safety, as the road cannot possibly be interfered with. In due course the train will enter track F, releasing line relay F. This makes a further break in the circuits of signal S1 and stick relay No. 1, and ensures that neither shall again operate until the train has left the section, which in this case comprises tracks E and F.

Now when the train has left track E there is no reason for maintaining the lock on points P4 and P3, and their release will enable the signalman to prepare the road for other trains. Accordingly, the operation of line relay E completes the back-lock release circuit of lever 1 through a contact previously closed by the release of stick relay No. 1. Lever 1 may then be replaced, thus freeing the mechanical locking of points P3 and P4.

When the train leaves track F, and so passes beyond the control of signal S1, line relay F will operate, closing the operating circuit of stick relay No. 1 if lever 1 has been replaced, or putting signal S1 to clear if the lever is left thrown. The operation of the stick relay closes the locking circuit for itself, and also restores the control of the back-lock on lever 1 to track M.

It will be apparent that by leaving lever 1 thrown, trains may be worked automatically through the junction from track M. This also applies to the other levers, and is a very valuable feature, as, by pulling the necessary levers for through traffic, a signal cabin may be left unattended except when switching or shunting operations are to take place.

The back-locks on the signal levers are so arranged that the levers may be replaced far enough to throw the signals to "danger" at any time, but can only be completely replaced and so free the mechanical locking of the points when this is safe. To economize in power, the back-lock circuits are taken through contacts on the switch-drums of their respective levers, and these contacts are closed during the mid-stroke only.

To overcome the difficulty introduced by the possibility of a signalman lowering the wrong signal in front of a train which approaches on a facing road, a sealed release key is provided in the back-lock circuits of such signals. The use of this key is rightly regarded as a serious matter, and has to be reported immediately.

Electric route-locking, combined with the continuous detection of signals through the points, obviates the necessity for facing-point locking bars and is especially valuable in more complex junctions where one signal may admit a train to several sets of points, as it combines complete safety with a minimum of lost time, since the locking is removed as soon as this is allowable.

Auxiliary Apparatus.

(*a*) *Route indicators.*—These are used at complex junctions to avoid a large number of levers in the signal frame. For example, a single signal lever and signal may admit trains to any of a number of platforms, the drivers being apprised of the route by the exhibition of an illuminated number below the signal. The various indicator circuits are detected through all the points on the respective routes to which they give access, and each route electrically back-locks the signal with which the indicator is associated.

(*b*) *Magazine train describer.*—A train describer is an aid to the expeditious working of junctions, as it shows in a signal cabin the destinations of all trains approaching on facing roads, so that the signalman may set the road correctly without it being necessary for him to observe code headlights.

Either at the previous signal cabin or at the previous station, there is a multiple-way switch, which is set by hand to correspond to the destination of each train as it passes. An illuminated indicator shows the driver if the description is correct, and, after passing the indicator, the train operates a special treadle. This treadle energizes a set of solenoids in the signal cabin, according to some particular combination determined by the position of the multiple-way switch at the previous cabin. These solenoids, when operated, push in pegs in the periphery of a drum, which rotates one step as each train is described. A set of contact fingers inside the drum, which rotate with it as the trains are described, rest on those pegs in a row which have been pressed in, and so complete circuits which cause an indicator above the lever frame to take up a position which gives the required description. As each train enters the junction track circuit another solenoid is operated, and this causes the contacts inside the drum to move back one step relative to the drum, thus cancelling the description, and setting up that of the next train, the cancelled pegs then being restored to normal. The device can thus store up the description of several trains, and will give them out as required. This train describer can be used to operate destination indicators on each station, thus adding to the convenience of passengers, and tending to reduce platform time.

(*c*) *Train-stops.*—Train-stops are fairly well-known pieces of apparatus, and can be used in conjunction with signals of all types. When a signal is at danger,

its associated train-stop raises a small arm just above the rail level, which will trip a valve on the brake pipe of a train attempting to pass the signal, and so arrest its progress. The train stops are usually wired in parallel with their associated signals.

(*d*) *Repeaters and fog repeaters.*—Repeater signals are installed where the view of the line ahead is poor, or where fast trains are run. They are distinguished from stop signals by a different colour scheme, and are usually controlled by contacts on the relay of the stop signal which they repeat. Where a repeater of the stop signal ahead is mounted on the same post as a stop signal, both stop signals control the repeater to prevent the anomaly of a repeater at "clear," and a stop signal at "danger," on the same post.

Fog repeaters were introduced by the Metropolitan Railway as an improved means of combating the effects of fog. They are placed on a level with the drivers' eyes, as near to the track as possible, and sufficiently far in advance of the stop signals which they repeat to allow drivers to pull up before reaching the stop signals. A fog repeater consists merely of a pair of lamps and lenses, and the lamp circuits are controlled in parallel with the lamps of the associated stop signal. The repeater lamps are also controlled by a switch placed at the nearest signal cabin or station, and can therefore be switched on as soon as a fog occurs, thus avoiding the delay occasioned by the calling out of fogmen.

The Effect of Faults.

In signalling work it is essential that faults shall never produce a false "clear" indication. Accordingly, the circuits are arranged so that the wiring must be intact, and the power must be on in order to hold a signal at "clear." Where any discriminatory action is effected by switch-drums, the possibility of circuits on both sides being simultaneously energized is guarded against by such an eventuality producing a short-circuit.

Power Supply and Consumption.

On electric lines, power for signalling is usually derived from the extra-high-tension mains through transformers and/or motor-generators set apart for the purpose. For isolated installations batteries are employed, and can be conveniently housed beneath the signal cabin.

Power signalling is quite economical, as 0·3 kW per mile of single track is usually sufficient.

THE IMPROVEMENT OF POWER FACTOR.

By the late* Dr. GISBERT KAPP, Past President.

(*Paper first received 4th April, and in final form, revised by* Prof. MILES WALKER, *24th October,* 1922; *read before* THE INSTITUTION *16th November, before the* NORTH-EASTERN CENTRE *13th November, before the* NORTH MIDLAND CENTRE *21st November, before the* LIVERPOOL SUB-CENTRE *27th November, before the* NORTH-WESTERN CENTRE *28th November, and before the* WESTERN CENTRE *4th December,* 1922.)

SUMMARY.

The economical limit of power factor improvement in relation to capital outlay. It is shown that if C is the capital cost of generating and transmission plant per kilowatt, and c is the cost of phase-improving plant per wattless kilovolt-ampere; then, writing $a = c/C$, it is economical (from the capital outlay point of view) to go on improving the power factor until $\sin \phi = a$, where ϕ is the angle of lag. The saving thereby effected is equal to $100[1 - \cos (\phi_0 - \phi)]$ per cent, where $\cos \phi_0$ is the original power factor before improvement. A practical example is worked out to show the operation of this rule. The synchronous motor and static condenser serving exclusively for injecting leading kVA are considered. The rotary converter and the synchronous induction motor serving the double purpose of supplying power and injecting leading kVA are dealt with and their province is described. Various methods of starting the synchronous induction motor are illustrated. The paper then goes on to treat of phase advancers of the rotating type connected to the slip-rings of induction motors. The effect of such advancers upon the performance of the induction motor is illustrated by several examples, and the change in the shape of the circle diagram is worked out. The author then proceeds to give an expression for the apparent capacity of his "vibrator" in terms of the constants of the machine, and shows how to arrive at the size of vibrator required to suit any given conditions. The last section of the paper deals with meters and tariffs. Various methods of indicating kW maximum demand and wattless kVA are described and particulars are given of the tariffs employed by various power companies. Observations are made as to the fairness of these to consumers who improve their power factor.

This paper deals with the use of such consuming devices, or the addition to existing consuming devices of such apparatus, as will diminish the phase angle between the vectors representing electromotive force and current. As in the majority of cases the current lags, the improvement in the power factor consists of the pushing forward of the current vector in the direction in which the vectors are rotating; but this is not necessarily always so. With the modern development of long-distance transmission, cases may arise where the current naturally leads, and then we want appliances not to advance it still further, but to retard it.

The primary object of power factor improvement is the better utilization of the electrical plant and, as far as the supply company is concerned, this includes the generator, step-up and step-down transformers, feeders, mains and switchgear up to the consumer's terminals. Whether the consumer's individual motors have a good power factor does not directly concern the supplier; all he asks is that the consumer shall take from his terminals a current nearly in phase with the voltage. This condition the consumer can always fulfil, either by employing good-power-factor motors, or by improving his plant by the addition of apparatus which will inject leading kVA into his terminals so as to bring up the general power factor of his installation to a reasonably good figure. That all consumers on a system should voluntarily incur the expense involved cannot be expected. The supplier must therefore make it worth their while, and thus the purely technical question of power factor improvement becomes tied up with the question of suitable tariffs.

This does not, however, exhaust the subject. Even assuming that the supplier were by a suitable tariff able to induce all his consumers to improve the peak-load power factor to unity, he would still have to face the question of his own power factor, not so much on account of the better utilization of the electrical plant as on account of his being under the obligation of supplying current at a stated voltage. In a small system with only a moderate diversity in the load characteristic between the consumers no difficulty arises, but in an extended system with long feeders the combined effect of reactance, resistance and capacity may be different on every feeder, and this effect will generally tend to make a difference of phase between current and voltage. Therefore, correcting devices should be used at the feeder ends. If the load on any particular feeder should be very light a device injecting permanently a given amount of leading kVA would cause the voltage to rise, and that is inadmissible; hence the necessity of an adjustable device such as an idle-running synchronous alternator. Examples will be given later.

APPARATUS USED FOR POWER FACTOR IMPROVEMENT.

The various appliances may be classified as follows:—

(*a*) Apparatus serving exclusively for injecting leading kVA at the end of a feeder, or at the consumer's terminals, for the purpose of improving the power factor of the system as a whole without affecting that of individual consuming devices. To this class belong the static condenser and the idle-running synchronous machine also known under the names dynamic condenser, rotary condenser, or synchronous condenser.

(*b*) The over-excited synchronous motor serving for the double purpose of producing motive power and injecting leading kVA into the system, and thus making up to a certain extent for lagging kVA taken by other consuming devices on the same system. To this class belongs also the a.c. to d.c. converter used in traction stations, the synchronous motor-generator, and the synchronous induction motor.

(*c*) The rotary or oscillating phase advancer acting

* Dr. Kapp died on 10th August, 1922.

on the slip-ring current of a motor so as to improve the power factor of this individual motor and, incidentally, also increase its overload capacity.

(*d*) The a.c. commutator machine or rotary phase advancer applied to the slip-rings of the motor and serving the double purpose of improving the power factor and acting as a slip regulator.

These various classes are considered further on, but before entering into questions of detail it is expedient to consider:

The Economical Limit to Power Factor Improvement in Relation to Capital Outlay.

The introduction of any kind of power factor improver to existing motors or other consuming devices necessarily involves some capital expenditure, but at the same time it reduces the capital cost of the electrical part of the generating and transmitting plant. Where, as in a private works, the supplier is also the consumer, the relation between extra expense on the consuming plant and saving of expense on the supply plant is direct and obvious. In the case of a supply company and its many consumers this relation may at first sight not be so obvious, nor so simple, because many non-technical considerations enter into the commercial business of buying and selling. Nevertheless, the relation exists. If the customer cannot participate to a reasonable extent in the benefit he confers by installing plant of good power factor, he will naturally refrain from doing so. On the other hand, if the customer demanded so large a reduction in tariff as to swallow up all the benefit, the company would naturally refuse to give that reduction and there would again be no phase-advancing, to the detriment of both parties. Thus the problem of the economic limit of power factor improvement is largely dependent on the cost of suitable apparatus, on the one hand, and the saving effected in the cost of saleable or available kW on the other.

When treating the question on broad lines and mathematically, we are therefore justified in taking the case of a private works, and we are indeed compelled to do so, because no mathematical formula can take account of the many side issues that may be raised between supplier and consumer which, even if not preponderant, must obscure the mathematical reasoning.

Let us then assume that a private works with a prospective peak load of 1 000 kW is to be established. The load may be provided for without the assistance of any provision for power factor improvement, and its cost will then be a maximum because the electrical part of the generating and transmitting plant is proportional to the kVA (not the kW) demand; or power-factor-improving apparatus may be used, in which case the generating and transmitting plant will be cheaper, but the consuming plant will cost more. The question is: How far should power factor improvement be carried so that the total cost becomes a minimum? The influence of power factor on the capital outlay for the prime mover is only indirect and is generally small, though it may be considerable with regard to working expenses. As we are now dealing only with capital outlay we disregard this part of the problem.

Let C = cost of generating and transmission plant per kW from the alternator to the points of supply at unity power factor.

ϕ_0 be the angle of phase difference between the current and voltage vectors when no phase-improving apparatus is used.*

$\frac{C}{\cos\phi_0}$ = corresponding cost per kW at a power factor of $\cos\phi_0$.

c = cost of phase-improving plant per wattless kVA injected into the supply terminals.

$a = \frac{c}{C}$

$\cos\phi$ = most economical power factor to which the whole system can be brought.

Both $\cos\phi_0$ and $\cos\phi$ are for peak load, not average power factors.

The total cost (excluding consuming devices) of the electrical plant is, per kW:

$\frac{C}{\cos\phi_0}$ . . . without power factor improvement.

$\frac{C}{\cos\phi} + aC\,(\tan\phi_0 - \tan\phi)$ with power factor improvement.

This becomes a minimum for

$$\sin\phi = a$$

and the total cost for a peak load of P kW is

$$PC[\sqrt{(1 - a^2)} + a\tan\phi_0]$$

instead of $PC/\cos\phi_0$ without power factor improvement.

The peak-load power factor to which the installation as a whole should be improved is

$$\cos\phi = \sqrt{(1 - a^2)}\,. \quad . \quad . \quad . \quad . \quad (1)$$

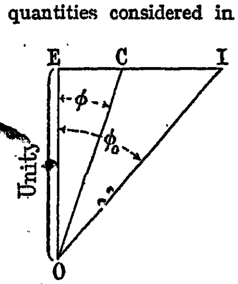
and the saving thereby effected is

$$100[1 - \cos(\phi_0 - \phi)]$$

per cent of the outlay for generating and transmitting plant without power factor improvement.

It will be seen from Equation (1) that the economical limit of power factor improvement does not depend on the power factor of the unimproved plant, but only on the ratio of the cost per kW of the original plant at unity power factor to the cost per wattless kVA injected by the phase advancer.

* The relations between the various quantities considered in this paragraph are apparent from the attached figure. If OE is taken as the direction of voltage vector, OI is the direction of the current vector before power factor improvement, and OC the direction of the current vector after power factor improvement. If OE is taken as unity and represents to scale the current required for one kilowatt at unity power factor, then OI = $1/\cos\phi_0$; EI = $\tan\phi_0$ = wattless current per kW delivered before improvement; EC = $\tan\phi$ = wattless current per kW after improvement. Then $(\tan\phi_0 - \tan\phi)$ represents the wattless current supplied by the power-factor-improving apparatus.—M. W.



The relation between α and $\cos\phi$ is simply that of a circle function, thus:

$$\begin{array}{lllll} \alpha = 0\cdot 1 & 0\cdot 2 & 0\cdot 3 & 0\cdot 4 & 0\cdot 5 \\ \cos\phi = 0\cdot 995 & 0\cdot 98 & 0\cdot 955 & 0\cdot 915 & 0\cdot 865 \end{array}$$

Since α is generally very small (say within the limits 0·1 and 0·3) power factor improvement may economically be carried fairly near to unity power factor, but should not be carried beyond it so as to make ϕ negative. This refers to the installation as a whole, but does not mean that any individual motor may not be worked with a leading power factor if thereby the overall power factor can be brought up to the economic limit.

From the above mathematical arguments we can deduce a few simple relations as to the cost of power factor improvement if done in the most economical manner as regards capital outlay.

Let K be the cost of the original plant without any improvement; K_1 the cost of the reduced generating and transmitting plant when a phase advancer is added; and A the cost of the phase-advancing plant itself. Let S be the saving in capital outlay through using phase advancers. Then the following relations obtain:

$$S = K - K_1 - A$$

$$K_1 = K\frac{\cos\phi_0}{\cos\phi}$$

$$A = K\alpha\cos\phi_0(\tan\phi_0 - \tan\phi)$$

$$\frac{A}{K_1} = \alpha\cos\phi(\tan\phi_0 - \tan\phi)$$

$$\frac{S}{K} = 1 - \cos(\phi - \phi_0) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The following table shows the saving in capital outlay effected by power factor improvement for a few values of α and $\cos\phi_0$.

$\cos\phi_0$ ..	0·6			0·7			0·8		
α	0·1	0·2	0·3	0·1	0·2	0·3	0·1	0·2	0·3
S/K in per cent	32	24	18	22	16	11	14	9	5

To form an opinion as to whether such a saving in initial cost of a private works for 1 000 kW peak load to be newly established is of importance, we may, by way of example, assume likely values for $\cos\phi_0$, C and α. A fair value for the peak-load power factor is 0·75. This might perhaps seem too low to some, but we must remember that not all the motors will be large or fully loaded even at peak time. There may be a number of small motors and these, or many of them, will generally be underloaded. Very often this is also the case with large motors. As a rule, consumers buy their motors rather too large because they want a good margin in torque in the case of short-time or sudden overloads. Hence the high full-load power factors which we find in motor lists cannot be expected under average running conditions. The installation may also contain some consuming devices (arc lamps or electric furnaces) with a bad power factor, so that in assuming the overall peak-load power factor to be 0·75 we shall not be far wrong. The estimate of the quantity C is much more uncertain. C includes cost of generators, connections to switchboard, all the switchgear, step-up transformers, protection devices, feeders, step-down transformers, some switchgear at the feeder terminals, and some mains up to the terminals to which the consuming devices are connected. Possibly transformers may be omitted, but heavier feeders will then be required, so that this item cannot make much difference in the total. The influence of size and speed of the generating units is more important; but here also the margin is not very large. It would hardly be safe to put down less than three units of 500 kW each so as to have one spare. If the process of working involved long spells of light load, bringing the conditions of working nearer to those obtaining in a large power station for general supply, four units might be even better because this would reduce working expenses. Another factor of uncertainty is the cost of the line, whether overhead or cable. It is obviously impossible to adopt a definite value of C fitting all cases, nor is it necessary, because from their own experience members can adopt the value which fits an actual case and can repeat the calculation here given merely by way of example. For the purposes of this example we may take $C = 12$, which means that the cost of the plant working at unity power factor comes to £12 per kW. The cost of power-factor-improving plant per kVA varies within wide limits; it may be as low as 10s. with a phase advancer applied to the slip-rings of a very large induction motor, or it may go up to £4 or £5 with static condensers. In order not to overstate the argument for phase-advancing, the cost is here taken at £3. This makes $\alpha = 0\cdot 25$. We thus find $\cos\phi = \sqrt{(1 - 0\cdot 0625)}$, or

$$\cos\phi = 0\cdot 965\,;\ \phi = 14° \ 30'\,;\ \phi_0 = 41° \ 25'\,;$$
$$\phi_0 - \phi = 26° \ 55'\,;\ \cos(\phi - \phi_0) = 0\cdot 89.$$
$$\text{Saving} = 100 - 89 = 11 \text{ per cent.}$$

The installation for the 1 000 kW peak load would cost $\dfrac{12}{0\cdot 75} =$ £16 per kW, or £16 000 in all for the electrical plant; but by adopting phase-advancing we improve the overall power factor to 0·965 and reduce the total cost to 16 000 minus 11 per cent of 16 000 = £14 240. Of this sum, about £12 500 is required for generating and transmitting plant, and the remainder, namely £1 740, for power-factor-improving plant.

The latter has to inject about 600 kVA. There are various ways in which this may be done. If there are some large motors among the consuming devices we might provide them with slip-ring phase advancers, or we might use synchronous motors, or self-starting synchronous induction motors, or we may provide squirrel-cage motors with static condensers, or we may use a combination of such means. The essential condition is that we must keep within the permissible expense of £3 per injected kVA. In other words we must not depart too widely from the rule $\sin\phi = \alpha$.

The Effect of Power Factor on the Working Cost of Generation and Transmission.

Whilst the peak load factor of consumers mainly influences capital outlay and efficiency, a bad power factor at lighter loads increases the cost of generation per unit. There is, morever, a reduction in the efficiency of generating and transforming plant. Both have certain losses, such as iron, friction and windage losses, which are dependent on their size but are independent of load; so that the overall efficiency of prime mover, generator and transformer is reduced by bad power factor. It must also be borne in mind that with small load and large kVA output more units must be kept in commission than would suffice with a good power factor; hence working costs are thereby increased. It is therefore to the supply company's interest that the consumer should have a good power factor not only at peak load, but also at lower loads.

The apparatus used for power factor improvement has already been briefly mentioned and will now be considered in somewhat greater detail.

The Rotary Condenser.

Over-excited idle-running machines employed solely for power factor improvement are not generally used by consumers. The only apparatus of this type I have seen was erected in 1896 by advice of the late Mr. Dobrovolsky at the Oerlikon engineering works in connection with the Buelach–Oerlikon transmission (23 km, 15 000 volts at first, later increased to 30 000 V) and this supplied current to the motors in the works. The firm informed me that a similar machine was at the same time supplied to the works of Messrs. Escher, Wyss and Co. in Zurich.

Recently two rotary condensers, each with an output of 3 000 kVA, have been installed by Mr. A. Dickinson* in connection with the Bombay hydro-electric works at the delivery end of the 100 000 V feeders.

Similar plant, but on a much larger scale, has been installed by the General Electric Company of America in connection with power transmission over very long distances.† Here the main object is phase adjustment, as explained in the beginning of this paper. The largest machine yet built has a capacity of 30 000 kVA when used to advance the phase of the current, and 20 000 kVA when used to retard the phase. It is a 10-pole three-phase 6 600-volt alternator running at a constant speed of 600 r.p.m. The following particulars taken from the text and the illustrations in the publication cited are of interest. The machine has salient poles in the rotor, the stator being the armature. The rotor has a diameter of 2·45 m and its core length is 2·05 m. The circumferential speed is no less than 77 m per second. The exciter is a 150 kW compound-wound generator giving a maximum current of 600 amperes for over-excitation. Thus only 0·5 per cent of the maximum kVA output is required for excitation. The output coefficient is 3·5 when the machine acts as a condenser, and 2·35 when it acts as a reactance. It is made self-starting by a damper winding on the rotor supplied by 30, 37½ and 45 per cent taps from the transformer. The damping winding during the start shields the main exciting winding from the effect of the rotating stator field, which would otherwise produce an excessive voltage in the exciting coils. To reduce the mechanical resistance at starting (which is due to the oil being squeezed out when the machine is at rest) oil under pressure is forced beneath the journals to make them float in oil before starting. The bearings are water cooled and the whole machine is cooled by air blast, the volume of air required being 37 m^3 per second. The temperature guarantees are a rise of 50 degrees C. in the stator and 80 degrees C. in the rotor measured by thermometer, and 10 degrees C. more if measured by thermo-couple.

Two smaller machines (each 12 000 kVA) were supplied by the same makers in connection with the 22 000-volt transmission of the Andhra Valley Power Company, Bombay. Owing to the higher ambient temperature (45·5° C.) the temperature-rise is limited to 45 degrees C. in the stator and 55 degrees C. in the rotor.

The author is not aware of any instance where a consumer drawing his supply from a thermic works has put up a rotary condenser on his own premises for power factor improvement; and the reason is not far to seek. The consumer has to pay not only for the energy he consumes in his motors, but also for that which he wastes in his rotary condenser, and that is a considerable amount. A rotary condenser of some hundreds of kVA cannot be worked with a smaller loss than a generator of equal output. The loss in kW may be somewhere between 6 and 7 per cent of the output in kVA. To realize what this means financially we may go back to the case of the private works of 1 000 kW peak load. At full load of 600 kVA (leading) the machine would require a supply of about 36 kW to cover its own losses; and although by decreasing the excitation to adapt the condenser to light-load conditions the copper loss in the armature might be decreased, all the other losses would remain the same, so that on the whole the loss would remain very much the same. Moreover, the attempt to economize by constant attention to the changing load conditions would introduce some extra cost of labour. We may thus base the financial argument on the supposition that the number of kW required to cover condenser losses remains constant during the whole time the installation is in use. With a load factor of 26½ per cent this means 2 300 hours per annum. In a year the rotary condenser would therefore waste 83 000 units. The energy supplied to the motors or other consuming devices amounts to 2 300 000 units. The energy wasted is therefore about 3·6 per cent of the energy utilized. If the load factor were lower than here assumed the percentage of wasted energy might exceed 4 per cent. It must also be borne in mind that the rotary condenser requires oil and renewal of brushes, perhaps occasionally some repairs, and certainly some slight amount of attendance. For interest, depreciation, maintenance and petty materials it is customary to reckon 15 per cent. With the machine costing (exciter and switchgear and foundation included) £3 per kVA, or in all £1 800, these charges come to £270, to which must be

* *Journal I.E.E.*, 1915, Vol. 53, p. 693.
† *General Electric Review*, 1920, vol. 23, p. 160.

added labour, which we shall not overestimate at £1 a week, thus bringing up the annual cost to £322. At 1d. per unit the charge for the supply would be, in round figures:

Useful energy	£9 600
Wasted energy	£346

To the latter figure must be added the £322, so that the rotary condenser costs annually £668, and to make in this case power factor improvement by rotary condenser a commercial proposition the supply company would have to give a rebate of at least 8 per cent. This is impossible. We may therefore consider the installation of rotary condensers by consumers to be financially unsound.

That rotary condensers are successfully used by supply companies is not due to financial reasons, but to the absolute necessity of giving their distant consumers a constant-voltage supply, for which purpose, in the present state of the art, the rotary machine is the only available apparatus.

The Static Condenser.

A condenser for power factor improvement as made by Messrs. British Insulated & Helsby Cables, Ltd., is composed of elements each of about 1 μF capacity suitably grouped to obtain the total capacity required and housed under oil in a tank, much in the same way as a transformer. Also, like a transformer, the static condenser requires no attention and has in this respect a great advantage over any rotary machine. It has the further advantage that its own waste of energy is exceedingly small. The limiting safe voltage on an element of the type mostly used is given by the makers as 600 V, but for certain purposes elements of smaller capacity with a safe voltage limit of 750 V are also made. The number of elements required depends on the terminal voltage, current and frequency.

Let E be the terminal voltage, ω the circular frequency (for the usual periodicity of 50, $\omega = 314$), P the desired leading kVA, c the capacity of one element in microfarads, and e the permissible voltage per element; then a simple calculation shows that the total number of elements is

$$n = \frac{P10^9}{\omega c e^2}$$

The cost varies inversely with the frequency and the square of the voltage per element. If the consumer's terminal voltage is sensibly less than 600 V it can be brought up to this figure by an auto-transformer. If it is more, it can be brought down to 600 V or up to a multiple of 600 V by the same means.

The power factor of a condenser is very small and, consequently, its inherent loss correspondingly low. The makers claim that it amounts in kW, on an average, to 0·5 per cent of its output in kVA. If a transformer is required there is, of course, an increased loss.

Fig. 1 shows the relation between temperature and power factor for different types of element, oil-immersed and tested at 250 volts and 50 frequency. In actual work the temperature-rise is stated by the makers to be 11 degrees C.

The control apparatus of static condensers consists mainly of oil-immersed switches with auxiliary contacts short-circuiting the condenser when the main switch is opened, and the usual no-volt and overload release and an ammeter.

The following data as to cost have been supplied to the author by the makers for a condenser equipment of 100 kVA output, including tank and switchgear, all at 50 frequency.

Voltage on supply terminals	600	440	440
Transformer	Not used	Used	Not used
Condenser voltage	600	600	440
Cost	£336 13s. 4d.	£468 8s. 4d.	£580 5s. 11d.

The Synchronous Induction Motor.

The practical application of the idea of using the same machine for the double purpose of providing motive power and at the same time injecting leading kVA into the supply terminals dates back some 30 years, when the Oerlikon Company employed a few such motors in their own shop, the current being derived

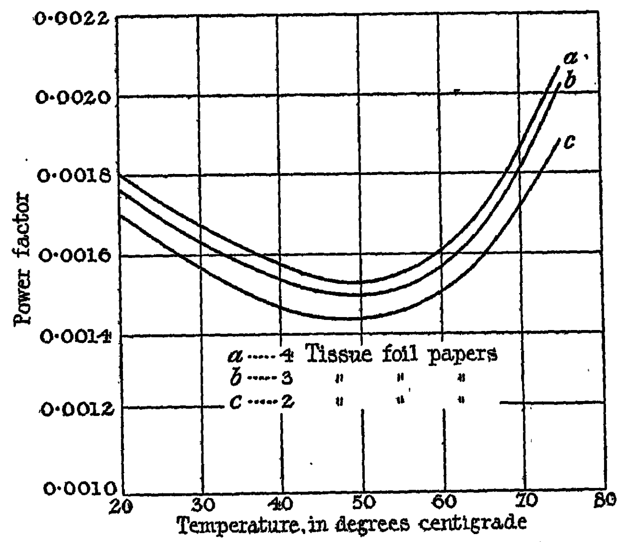


FIG. 1.—Power factor tests on Helsby condenser elements; made at 250 volts and 50 cycles.

from the Buelach line already mentioned. It is, of course, convenient that a motor for this purpose should be made self-starting and self-synchronizing. If the machine is provided with a wound rotor, like an induction motor, it can be started with a resistance inserted in the rotor circuit, and when it is nearly up to speed a direct current can be passed through the rotor winding so as permanently to magnetize the poles and convert it into a synchronous motor. In order that the motor

when so excited shall jump into synchronism the slip must be small and the moment of inertia not too great.* Almost every dynamo maker is ready to supply such motors.

The various makes differ in detail, but the main principle is the same. In some cases the direct current can be applied during the starting period, so that the process of starting is as simple as with an ordinary induction motor.

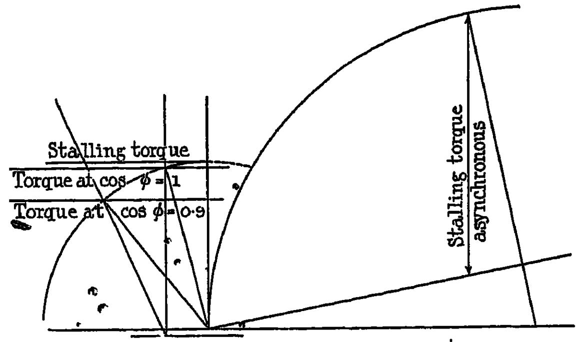


FIG. 2.—Locus diagrams of synchronous induction motor (original power factor 0·89).

The rotor may have salient poles as in an alternator, or it may have non-salient poles. In the former case the starting torque is smaller than with a non-salient-pole type; and for this reason, as also for the convenience of using standard frames and stampings, it is generally found that to convert the induction motor to synchronous working is more advantageous than the opposite process, namely, to start with the design of a synchronous machine and convert it into an induction motor.

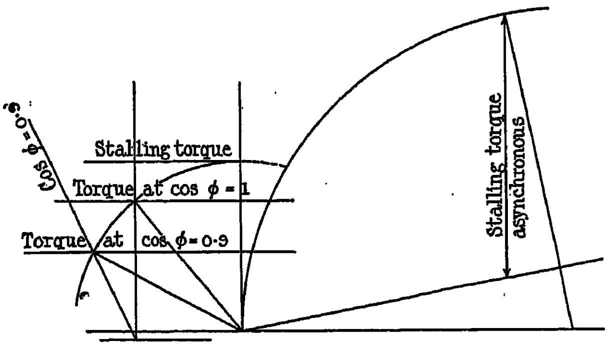


FIG. 3.—Locus diagrams of synchronous induction motor (original power factor 0·73).

The working condition of the motor can be represented by a circle diagram much in the same way as that of an ordinary induction motor, only that in the self-starting motor we have two locus curves, the one for the synchronous and the other for the asynchronous condition. With d.c. excitation fixed at a value just sufficient to give full load at unity power factor (with no saturation in the teeth), the locus for the synchronous condition has a smaller radius. The original power factor of the induction motor to be converted has a considerable influence on the stalling torque in the synchronous condition. This will be seen from Figs. 2 and 3, drawn approximately to scale for the same excitation at all loads, and therefore the same heating in the rotor.

In Fig. 2 the natural power factor of the induction motor is 0·89 and in Fig. 3 it is 0·73. In both diagrams the vectors are inserted for unity and 0·9 leading power factor. Taking as a datum for comparison the torque of the induction motor as 100 in both cases, the diagrams show the following working conditions for constant excitation:

Original full-load power factor ..	0·89	0·73
Full-load torque	100	100
Torque at unity power factor ..	100	86
Torque at 0·9 leading power factor	84	53
Margin to stalling torque in the synchronous condition	Practically none	27
Margin to stalling torque in the asynchronous condition	70	73

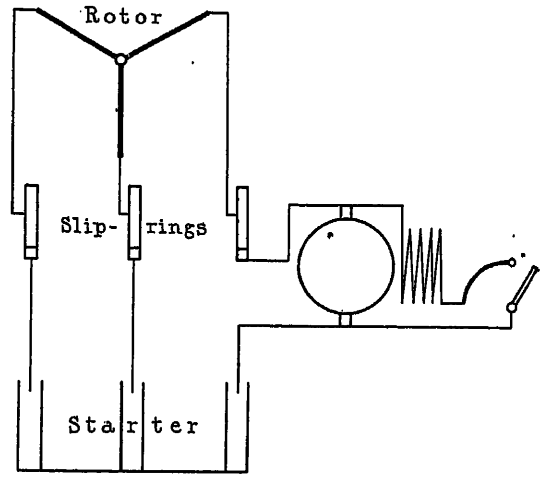


FIG. 4a.—Method of starting a synchronous induction motor (British Westinghouse, 1913).

The dotted part of the synchronous locus circle indicates an unstable condition. When the motor falls out of step it continues to run as an asynchronous motor. It synchronizes again when the load has fallen below stalling load. If the motor is designed for full load at 0·9 power factor it will not fall out of step so easily, but then its kVA capacity must be greater than that of an ordinary induction motor. For this reason, and also because an exciter is required, the cost of a synchronous induction motor must always be greater than that of an ordinary induction motor; and the difference in cost must be the greater the smaller the leading power factor required for full normal load. Examples are given later. Two conditions are necessary for a motor to self-synchronize, namely, a small natural slip and a small mechanical moment of inertia. Modern practice is to put sufficient copper into the rotor to make the slip about 1 per cent and to keep down the moment of inertia to the lowest possible

* See paper by E. ROSENBERG, *Journal I.E.E.*, 1913, vol. 51, p. 62.

value; then the motor readily synchronizes, even under load or overload.

The switchgear between the rotor slip-rings and the starter is shown diagrammatically in Fig. 4 for some of the systems adopted by various makers. Fig. 4*a* illustrates the simple arrangement in which the direct

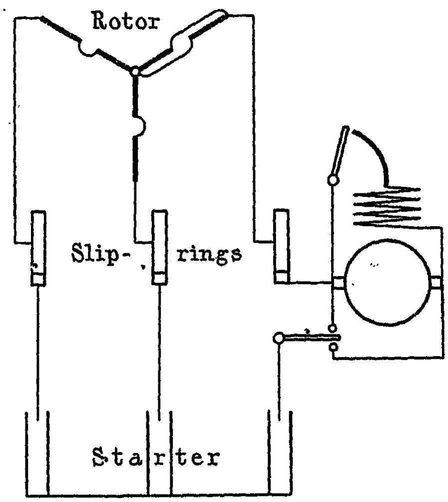


FIG. 4*b*.—Method of starting an Oerlikon synchronous induction motor.

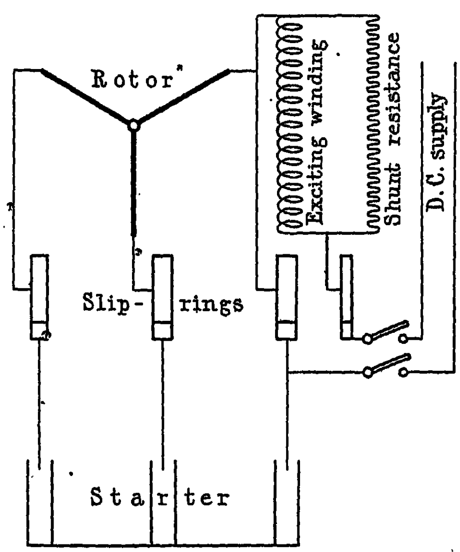


FIG. 4*c*.—Method of starting a Siemens-Schuckert synchronous induction motor.

current is passed down one phase and up the other two in parallel. The stator circuits are not shown. The stator may, in order to reduce disturbance of the line at starting, be arranged in the well-known way for starting in star and running in delta; but this is applicable to all types and need not be considered here.

If the rotor has a three-phase winding it is obvious that one phase must carry the full exciting current, whilst the other two phases each carry half of it. Let n be the number of turns and ρ the resistance per phase, then the loss of power in the three phases when working asynchronously with a phase current I will be $3\rho I^2$, and the axial excitation will be $2nI$.

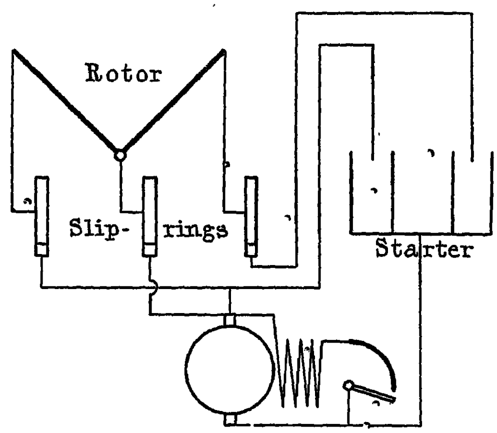


FIG. 4*d*.—Method of starting a Crompton synchronous induction motor.

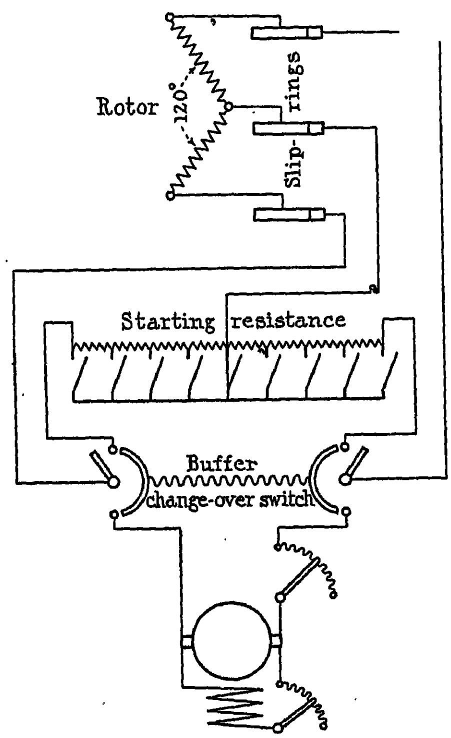


FIG. 4*e*.—Method of starting a Lancashire Dynamo and Motor Co. synchronous induction motor.

Let i be the direct current to produce the same loss; then we have

$$1 \cdot 5\rho n i^2 = 3\rho n I^2 \quad \text{and} \quad i = \sqrt{2} I$$

The exciter must therefore give about 40 per cent more current than the normal slip-ring current in the asynchronous condition. The axial excitation produced will be about 5 per cent greater, but as the rotor teeth must be well saturated there is no proportional increase in the field. On the other hand there is

unequal local heating. To get over this difficulty the Oerlikon plan (Fig. 4*b*) is to arrange the winding in one phase in two parallels, each of $\frac{1}{2}n$ turns. Then the heating is uniform all over the rotor and the excitation is the same as with alternating current. The exciting current is double the alternating current at the slip-rings. In the asynchronous condition the halving of the number of turns in one phase introduces some dissymmetry, but as there is always plenty of starting torque this is of no importance.

In a system devised by Messrs. Siemens-Schuckert (Fig. 4*c*) we find an attempt to reduce the amount of direct current for excitation by providing a separate winding for excitation, having a larger number of turns than the three-phase winding. The rotor has salient poles, but with the pole-shoes so wide (95 per cent of the pole-pitch) that the starting winding, which is housed in the pole-shoes, acts almost as in a motor with non-salient poles. The exciting winding is, as in

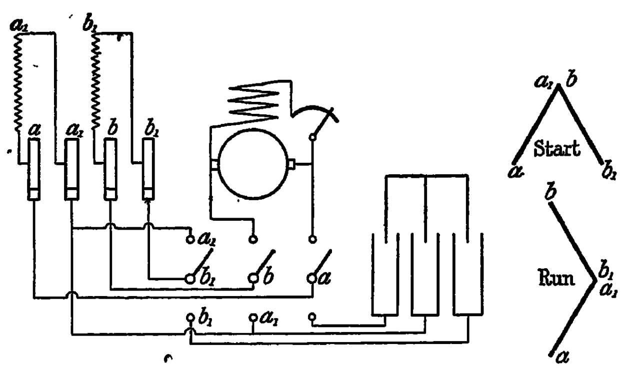


FIG. 4*f*.—Method of starting an English Electric Co. synchronous induction motor.

any synchronous machine, placed on the magnet cores and the excitation is so great as to produce a high degree of saturation in the rotor teeth. At starting, a very high voltage is induced in the exciting coils, so that it is necessary to introduce for its protection a shunt resistance permanently coupled in parallel with it. This resistance has to be carefully selected so that on the one hand it shall lower the terminal voltage over the exciting coils sufficiently and, on the other, it shall not absorb too large a proportion of the power supplied by the exciter.

The exciting arrangements employed by the Metropolitan-Vickers Company have recently been dealt with in Mr. Carr's paper* and therefore need not be described in detail here. They are all more or less amplifications of the principle shown in Fig. 4*a*.

Messrs. Crompton use a two-phase winding on the rotor, with the star point carried to a slip-ring, so that, in all, three slip-rings are required. The advantage of this arrangement is that, although there may be a high voltage on the two outer slip-rings, the voltage on the neutral or star slip-ring, and therefore on one terminal of the exciter, is no higher than the exciting voltage, as will be seen on tracing out the exciter circuit (Fig. 4*d*). Thus the whole of the exciter is protected from the open-circuit slip-ring voltage. A further advantage is that the whole of the rotor copper is loaded to the same current density. The makers claim that the machine in its asynchronous condition will start against $2\frac{1}{2}$ times full-load torque. The exciter is permanently in circuit and, by adjustment of its shunt rheostat, the leading power factor at various loads can be regulated.

The standard type of starting and synchronizing gear used by the Lancashire Dynamo and Motor Co. is shown diagrammatically in Fig. 4*e*. The rotor has also a two-phase winding, but with 120° angular displacement of the phases, each acting at starting as an independent single-phase winding, whilst at synchronism the middle slip-ring is out of circuit so that the two windings give together an excitation equal to $\sqrt{3}$ times the ampere-turns of one phase. The change-over from the asynchronous to the synchronous condition is made

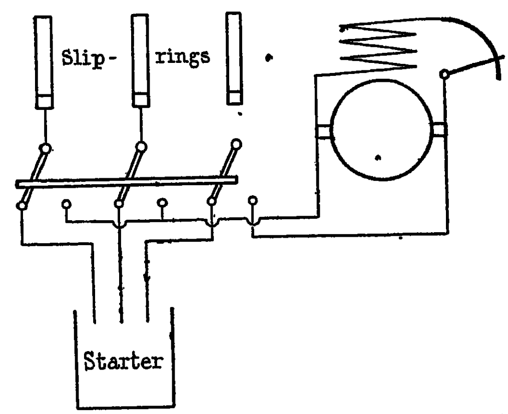


FIG. 4*g*.—Method of starting a General Electric Co. synchronous induction motor.

via a "buffer resistance," as will be seen from the diagram.

By an ingenious arrangement of change-over switchgear the English Electric Co. obtain the advantage of the full starting torque due to a three-phase rotor, combined with equal current loading in all the rotor copper when the rotor acts as a single-axis field magnet. The rotor has only two phases, but these may be coupled to form an open delta for starting, when the electrical angle between the two phases is 60°, and by reversing one phase the electrical angle may be altered to 120°, when the excitation given is $\sqrt{3}$ times the ampere-turns in one phase.

The arrangement is shown diagrammatically in Fig. 4*f*. There are 4 slip-rings marked a, a_1 and b, b_1 corresponding to the four terminals of the A and B phases (in open delta the third phase is omitted). To facilitate the tracing out of the connections the switch contacts are similarly labelled. The small key diagrams show vectorially the connections for "start" and "run." At starting the switch is on the lower contacts, and after all the starting resistance has been short-circuited the switch is thrown on to the upper contacts.

Fig. 4*g* shows diagrammatically the exciting circuit adopted by the General Electric Co. for their syn-

* *Journal I.E.E.*, 1922, vol. 60, p. 165.

chronous induction motors. The rotor is star connected, and the connection with the exciter is such that one phase carries the total exciting current, whilst the other two phases each carry half that current. Strictly speaking, the one phase may therefore be called overloaded; but in reality it is not so. It would be more correct to say that the other two phases are underloaded. This is, however, an unavoidable consequence of the necessity of restricting the slip to a smaller value than in an ordinary induction motor in order to ensure quick and certain synchronizing, so that the extra copper in the rotor would have to be provided in any case.

Construction and Performance of some Synchronous Induction Motors.

A characteristic feature in the design of all such motors is that to ensure stability the air-gap is made larger than in ordinary induction motors. A further characteristic is that the rotor teeth are highly saturated. Otherwise there is no important difference in the magnetic

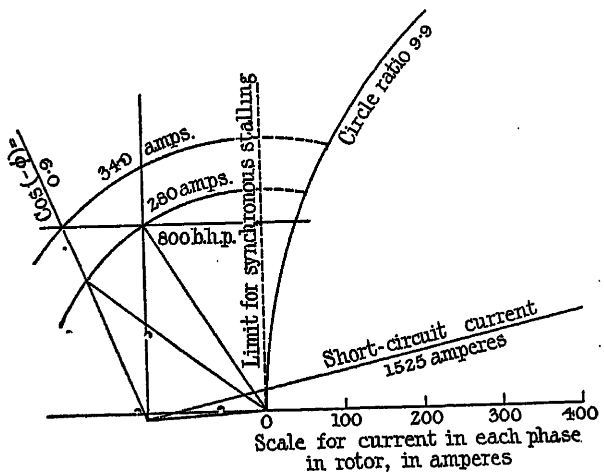


FIG. 5.—Circle diagram of 800 b.h.p. Crompton synchronous motor; 2 200 volts, 25 cycles, 250 r.p.m.

circuit, so that the same type of frame may be used for either the synchronous or the asynchronous motor. Electrically there is the difference that, with a view to quick and certain synchronizing, more copper is put into the rotor, and the current-carrying capacity of the slip-rings and their brushes must be greater. Short-circuiting of slip-rings is impossible. In most motors some excitation may be left on during the starting period. The synchronous stalling torque is always smaller than the asynchronous, but when the load torque exceeds the former the motor runs on as an asynchronous machine with a low, lagging power factor until the load has fallen, when the motor again jumps into step. The efficiency is a little lower owing to the greater loss in excitation. The open slip-ring voltage is higher than in an ordinary induction motor and may reach 2 000 volts.

The following data will serve to give a more precise meaning to the above general statements.

800 *b.h.p. Crompton motor:* 2 200 line volts; 25 cycles; 250 r.p.m. stator three-phase; rotor two-phase; air-gap 4·5 mm; open slip-ring voltage 1 300 V to earth; exciting current per phase, according to load and power factor, up to 340 amperes, or 680 amperes on the star-point slip-ring. The circle ratio (ideal short-circuit current divided by open-circuit current) is 9·9. From the locus diagram (Fig. 5) the working condition at any power factor and load can be determined.

The following table is given by the makers to show the performance of this motor:

Output	Line volts	Line current	Exciting power	Efficiency*
b.h.p.	V	A	per cent	per cent
800	2 200	168	1·7	93
800	2 200	188	2·9	92

* At half-load the efficiency is 1 per cent lower.

The makers state that the increase in cost over an ordinary induction motor would be approximately 20 per cent when designed for unity power factor, and 30 per cent for 0·9 loading power factor.

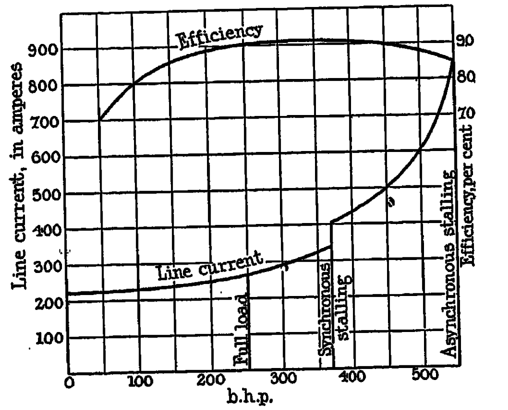


FIG. 6.—Performance curves of 250 b.h.p. Oerlikon synchronous induction motor; 500 volts, 50 cycles, 750 r.p.m.

Motors of the Lancashire Dynamo and Motor Co. Ltd. —The salient-pole type (used when only a light starting torque is required) has a starting winding housed in the pole-shoes, and this winding also acts as a damper to protect the field winding from excessive voltage. For heavy starting torque the non-salient-pole type is used, but has no additional squirrel-cage winding, as the field winding itself acts as a starting winding. Dampers are generally not required, but, if desirable, a damping effect may be produced by short-circuiting part of the rotor winding. The open slip-ring voltage varies between 1 400 and 2 000. The non-salient-pole type is started in the manner shown in Fig. 4e. The individual switches in the solid starter resistance are successively closed by a reciprocating motion given by hand to a starter handle which, in its last movement, also puts the motor into synchronism by first connecting up the resistance (marked "buffer" in the diagram)

across the rotor terminals, then taking the rotor off the starter resistance, switching it on to the exciter circuit and finally opening the buffer circuit. A second handle serves for returning the starter to the starting position.

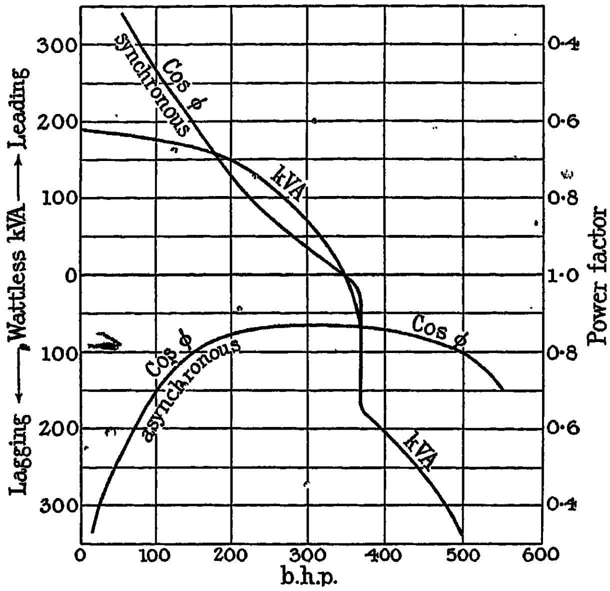


FIG. 7.—Performance curves of 250 b.h.p. Oerlikon synchronous induction motor; 500 volts, 50 cycles, 750 r.p.m.

Interlocks are provided for preventing the closing of the main stator switch unless the starter is in the starting position. As regards the excitation required for amount of power factor correction required. Taking, however, the usual case that a leading power factor of 0·9 is desired, the makers estimate that the increase may be taken to be one-third the cost of an asynchronous motor of the same power.

250 *b.h.p. Oerlikon motor:* Terminal voltage 500; 50 cycles; 750 r.p.m.; 0·9 leading power factor. The starting resistance is solid (the starter shown in Fig. 4*b* has been represented as a liquid starter merely to preserve as far as possible uniformity of representation) and the two-way switch in Fig. 4*b* is replaced by the usual three-phase starting switch worked by a hand-wheel. Another hand-wheel serves to adjust the excitation. The starting and regulating gear is housed in a cast-iron case permanently attached to the motor frame. The exciter is mounted overhung on the motor shaft. The performance of the motor is shown by the curves in Figs. 6 and 7.

550 *b.h.p. English Electric motor:* Terminal voltage 1 000; 50 cycles; 428 r.p.m.; unity power factor at full load and leading power factor at smaller loads; constant excitation at 44 volts, 220 amperes; synchronous stalling point at 1·7 times full load. The tooth density is very high, so that there is a great difference in the rotor current when the motor works asynchronously and when it works synchronously with d.c. excitation in the rotor. The high saturation makes the field stable, and the fact that the axial excitation is provided by two coils with their axes 120° (instead o 180°) inclined to each other has a beneficial effect on the field form. Fig. 8 shows the locus curves of this motor, and Fig. 8*a* the performance curves.

250 *b.h.p. General Electric motor:* Terminal voltage, 440; 50 cycles; power factor from unity to 0·9 leading

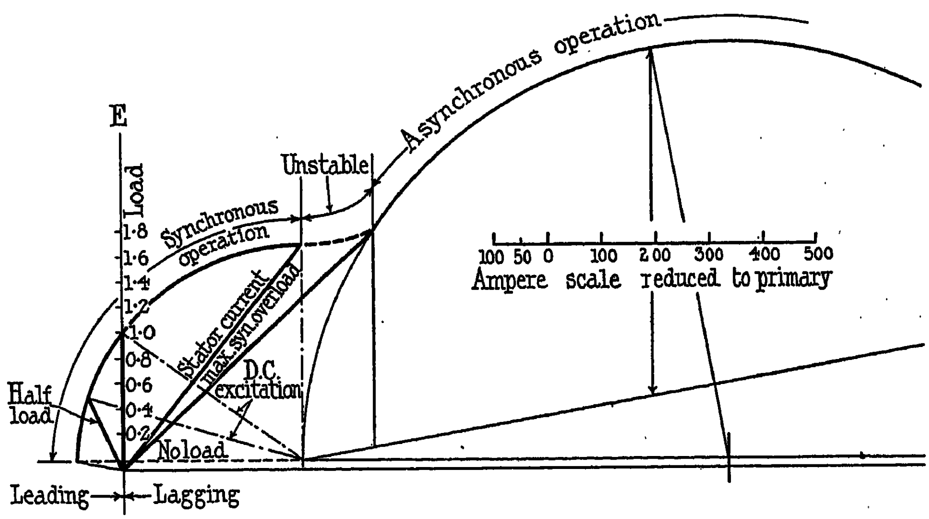


FIG. 8.—Circle diagram of an English Electric Co. 550 b.h.p. motor.

0·9 leading power factor motors, the makers have given me the following examples:

650 b.h.p. exciter: 400 amperes, 40 volts
320 b.h.p. exciter: 230 amperes, 60 volts

The increase in cost of the synchronous over the asynchronous machine is largely dependent on the at full load, according to excitation; 375 r.p.m.; open slip-ring voltage, 1 140; slip, 1·06 per cent; diameter of armature, 120 cm; core length, 25 cm; air-gap, 2·5 mm. The exciter is mounted on the motor shaft and has a maximum output of 5·6 kW.

Fig. 9 shows the performance of this motor as a function of the output in brake horse-power. A and B

are power-factor curves at constant excitation; C is the efficiency curve if the excitation is adjusted to give unity power factor at all loads, and D is the efficiency curve if the excitation is adjusted to unity power factor at full load, but not varied for smaller loads.

starting resistances. The currents through the rotor windings are symmetrical and no second field can therefore be produced. The motor designed for an (8 + 4)-pole cascade is started as an 8-pole machine and when near synchronism three of the slip-rings are

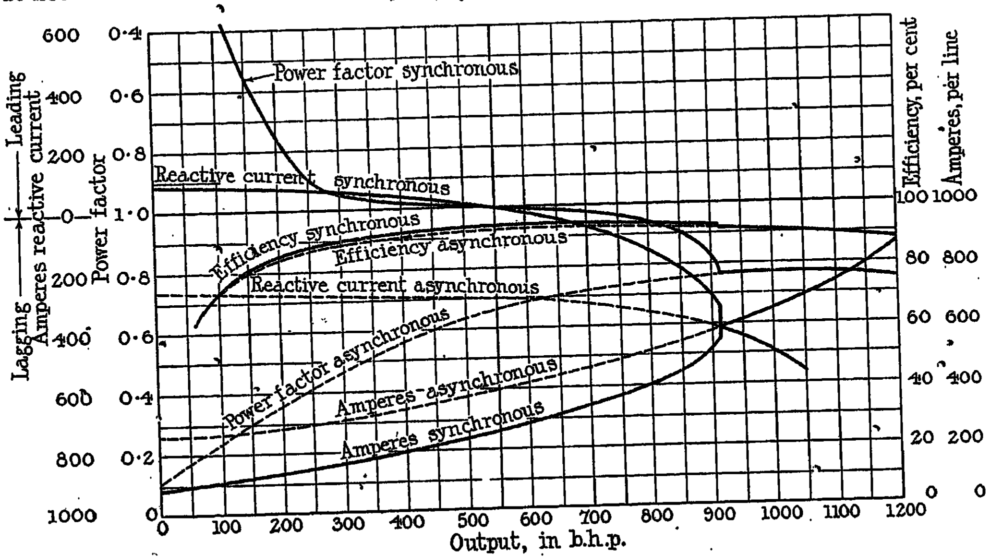


FIG. 8a.—Performance curves of an English Electric Co. 550 b.h.p. motor.

225 b.h.p. Sandycroft single-field cascade motor.—The stator in Mr. Hunt's self-starting synchronous cascade motors (Fig. 9a) is provided with two star-coupled windings in parallel, and the d.c. excitation is introduced between the two star points.* The rotor winding consists of a six-sided mesh with star coils

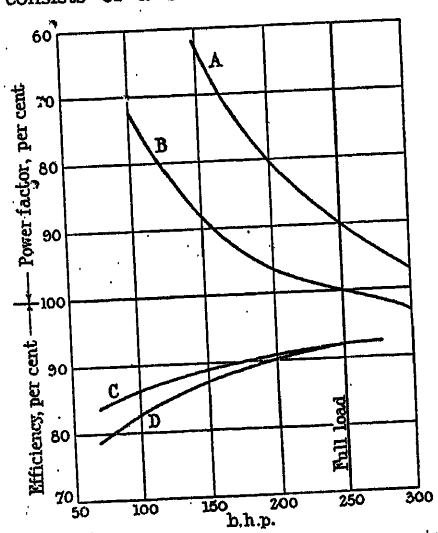


FIG. 9.—Performance curves of a General Electric Co. 250 b.h.p. motor.

tapped into it at equally spaced points. The terminals of these coils are brought out to six slip-rings. Opposite rings are connected in pairs across three independent short-circuited and the remaining three are open circuited. This action converts the winding into an interconnected star-mesh system and results in the production of an auxiliary 4-pole field. The switch used for changing the rotor connections also connects the star points of the two parallel stator windings to the d.c. exciting circuit, producing a stationary 4-pole field. At synchronism the 4-pole rotor field rotates relatively to the rotor iron at 500 r.p.m. and, as the rotor itself has the same forward speed, the two 4-pole fields in stator and rotor are stationary in space and lock together so that the motor works as a synchronous 12-pole machine. Efficiency and power-factor curves are sown in Fig. 9b.

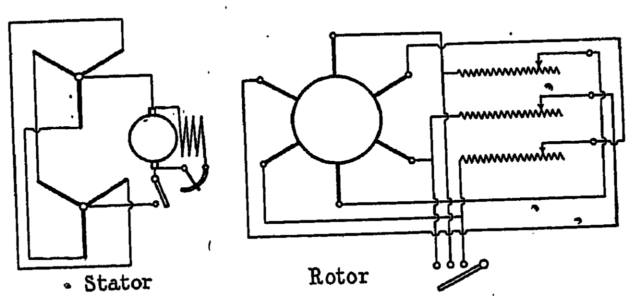


FIG. 9a.—Connections of a Hunt (8 + 4)-pole cascade motor.

THE ROTARY CONVERTER AS POWER FACTOR IMPROVER.

At first sight the rotary converter appears to be an admirable appliance to inject leading kilovolt-amperes into the supply line, but on closer consideration of its working condition it will be found that its use in this

* See paper by Mr. L. J. HUNT, *Proceedings of the South Wales Institute of Engineers*, vol. 35, p. 309.

direction is rather limited on account of the rapid increase of the copper losses in the armature with an increase of the wattless component given to the line. The increase in output of a rotary converter as compared with a simple d.c. generator is due to the fact that the armature winding has to carry only the difference between the motoring alternating current and the

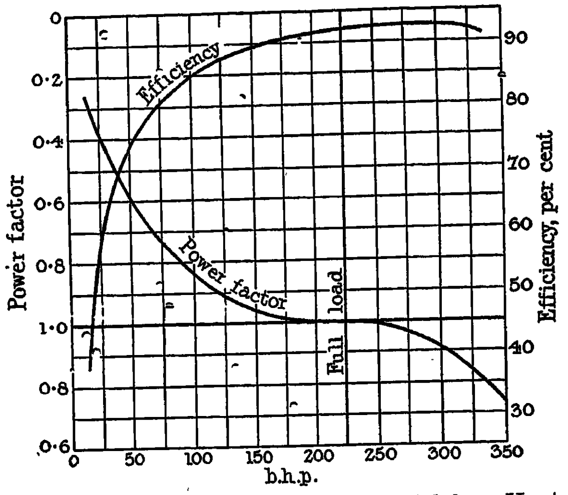


FIG. 9b.—Performance curves of a 225 b.h.p. Hunt (8 + 4)-pole cascade motor.

generated direct current. For unity internal power factor this difference is a minimum. The external power factor at the terminals is then about 0·98 lagging. To get unity at the terminals the internal power factor must be of the order of 0·98 leading. To get a leading power factor at the terminals the internal power factor

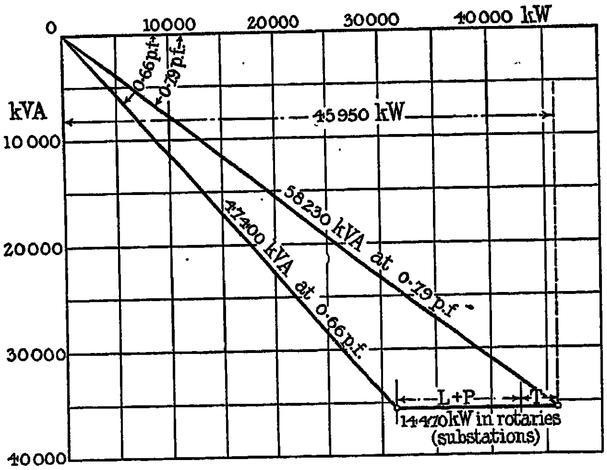


FIG. 10.—Load vectors of Birmingham electric supply.

must be correspondingly smaller, which means that the wattless component must be larger. Since the amount of heating increases as the square of the wattless component, it follows that power factor improvement can only be obtained at the sacrifice of output. The copper loss in a six-phase converter is smaller than in a three-phase one, and, if we refer the increase of losses due to the leading current to the normal loss at unity power factor, we find that the percentage increase of loss is larger in a six-phase than in a three-phase converter. Thus if the field excitation is increased so as to induce a 30 per cent wattless component, the copper loss for full output would be increased by about 18 per cent in a three-phase and by about 30 per cent in a six-phase converter. To keep within the heating limit the output would therefore have to be reduced to 92 per cent and 88 per cent respectively of the permissible output at unity power factor. This is rather a high price to pay for the injected kilovolt-amperes. Economically it is better not to use the converter for giving to the line leading kVA, but to be content with taking from the line true kW and thus raising the general power factor of the system by increasing the watt load. Moreover, a converter excited to unity power factor will scarcely influence the line voltage at all, whilst a converter injecting leading kVA may have some disturbing influence.

As an example of the beneficial influence of a converter load on a general supply system we may take that of the City of Birmingham, to whose engineer, Mr. R. A. Chattock, the author is indebted for the following particulars and for the vector diagram shown in Fig. 10. The total capacity of the rotary converters is 9 800 kW at unity power factor. All rotary converters are provided with means to vary their power factor down to 0·97 leading, but Mr. Chattock considers it hardly safe to go beyond this. Generally the converters are worked at unity power factor.

The power factor improvement is shown in the following table referring to the time of heaviest load, which occurred at 4.30 p.m. on the 17th December, 1920. In the vector diagram P and L mean d.c. power and lighting load, and T means traction load.

Total a.c. load on all generating stations	58 230 kVA at 0·79 power factor.
Substations' load, at the same time, taken up by all substation rotary converters running at approximately unity power factor, of which 11 213 kW is power and lighting and 3 261 kW is traction	14 474 kW.
Estimated e.h.t. supply outside substations on 17 December, 1920	47 400 kVA at 0·66 power factor.

SLIP-RING PHASE ADVANCERS.

If an electromotive force of slip frequency is introduced in the correct sequence into the slip-rings it will shift the rotor current forward. To ensure that the injected E.M.F. shall have the correct frequency, the rotor current itself is made to generate it; and to ensure the correct sequence is merely a question of making the appropriate connections between the phase advancer and the slip-rings. The interaction between the stator and rotor causes the leading kVA injected into the rotor to be translated into the line, and thus a comparatively small amount of kVA given to the rotor becomes a large amount of leading kVA given to

the line. We may take as an example a 500 kW motor with, say, 1·5 per cent slip. If it is desired to inject into the line 50 per cent of the true power as wattless kVA, the line would require a supply of 250 leading kVA. The working condition of the motor would not be altered; the slip and the overload capacity would remain as they were. If we inject a certain amount of leading kVA into the rotor the working condition of the motor will be altered. The slip must increase because the slip E.M.F. must now cover not only any additional ohmic loss, but also the quadrature component of the E.M.F. of the phase advancer. The slip of 1·5 per cent may thus become increased to 2·5 per cent and the translating ratio of the interaction between stator and rotor will no longer be 100 to 1·5, but 100 to 2·5. That is to say, for every kVA injected into the rotor the line benefits by 40 kVA. Neglecting losses, which are very small, a phase advancer having an output of 6·3 kVA will benefit the line to the same extent as a static or rotary condenser giving it 250 kVA. At the same time the overload capacity of the motor is increased.

There are two types of slip-ring phase advancer in use: the rotary and the oscillatory. The former is an a.c. commutating machine which must be driven from some external source of power, the latter is a d.c. machine which requires no external driving, but needs d.c. excitation from an external source.

Rotary Type of Phase Advancer.

The general principle of the rotary phase advancer is shown in Fig. 11 for a 2-pole three-phase machine. A, B, C are the stator exciting coils (the diametrically opposite poles are not shown, in order to avoid complication), R represents the armature, and K the commutator with the three brushes, a, b, c. In the position shown, the brushes are in the polar axes and therefore the armature exerts no torque. If the brushes are displaced in one sense, the machine gives torque in the opposite sense and acts as a motor taking power from the slip-rings, at the same time injecting a certain amount of leading kVA into the slip-rings. This property of the rotary advancer can be used in cases where the main motor is provided with a flywheel in order to cope with heavy peak loads, when a considerable slip must be allowed. Then part of the slip energy may be recovered instead of wasting the whole of it in slip resistance.

Where only phase-advancing is required the brushes remain in the axial position; the impressed flux and that created by the armature current are then in line, and by giving the armature a winding of sufficient turns the whole of the flux required can be produced by the armature winding itself, so that a stator with the coils A, B, and C becomes unnecessary.

This is the principle on which the Scherbius rotary phase advancer is constructed. The machine has no stator, but the iron core of the armature is radially extended beyond the armature conductors so that the rotor iron outside the winding performs the office of an external stator. Since the magnetic reluctance of the air-gap is thus avoided, the advantage of a strong field with only a moderate excitation is secured. On the other hand there is the disadvantage that the commutation necessarily takes place not in the neutral space, but in the strongest part of the field, making the commutation more difficult than in an ordinary d.c. machine. The fact that not a direct but an alternating current must be commutated is of little importance, because the frequency of this current is so low that the condition as regards commutation is practically the same as with direct current. The arrangement of this machine is diagrammatically illustrated in Fig. 12.

If the rotor is at rest the machine acts simply as a choking coil. The currents introduced by the three brushes produce a rotating field having an angular velocity corresponding to the slip frequency. The self-induced E.M.F. lags behind the current by a quarter period. If, now, the armature is rotated by external power with slip frequency, there is no cutting of field lines by the armature winding and the machine acts simply as a dead resistance. By increasing the impressed speed, so that the winding rotates with a speed greater than that of the field, the E.M.F. generated changes sign, that is to say, it leads relatively to the current by a quarter period. The faster the armature

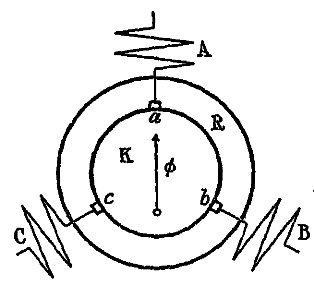


Fig. 11.—Diagram of phase advancer with field winding.

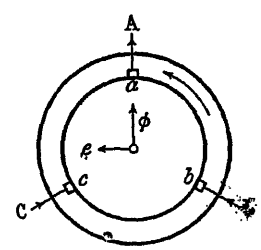


Fig. 12.—Diagram of phase advancer without field winding.

is driven the greater is the phase-advancing effect on the rotor currents of the motor.

The principle on which a locus diagram of an induction motor with slip-ring phase advancer may be constructed has been given in a previous paper * and need not be repeated here. It is, however, interesting to note that the theoretical locus curve deduced on the assumption that there is no saturation is beneficially altered by so designing the Scherbius armature that at full load there shall be considerable saturation. Referring to Fig. 4 of the previous paper, ES, the ohmic voltage loss in rotor and advancer, is approximately proportional to the phase current † and also to the excitation producing the leading E.M.F., but this E.M.F. (SB in Fig. 4) is not strictly proportional to the current. As the saturation increases, the field increases only according to the magnetization characteristic, and the E.M.F. injected increases a little less than the field because with increasing load the slip increases and the excess of armature

* G. Kapp: "Phase Advancing," *Journal I.E.E.*, 1913, vol. 51, p. 252.

† The proportionality would be perfect if it were not for the fact that the contact-drop at the brushes and slip-rings does not follow strictly Ohm's law. For the sake of simplicity this disturbing influence is here neglected. In the discussion of the oscillating phase advancer the increase of resistance with diminishing current is, however, taken into account.

speed over the speed of the revolving field becomes a little smaller, especially if the advancer is driven by the motor itself. The effect of saturation can be taken account of in a very simple manner, whilst that of speed variation is not serious and can also be easily corrected. Let, in Fig. 13, OE be the no-load current and EC the radius of the Heyland circle. ES represents the ohmic voltage-drop in one phase. By a suitable scale it may also represent the excitation on the magnetizing characteristic Eee. With constant speed of cutting, BS represents, then, also the injected E.M.F. Draw EB and prolong to C′. This is the centre from which the larger circle of Fig. 4 (of the quoted paper) must be struck. Mark the point D on the Heyland circle so that ED represents the phase current to which the voltage-drop ES corresponds, and draw a circle with E as centre. Where this circle intersects the circle struck from C′ is the locus. EB represents the slip volts and from this can be found the slip. Having determined the slip we can calculate what small reduction in SB is required to account for diminished relative speed between the rotating flux and the rotating winding and repeat the construction. The resulting locus curve has the character shown in Fig. 13. The effect of saturation is to avoid excessive phase-advancing at heavy load and yet obtain a satisfactory power factor at lighter loads. As will be seen from the locus curve, the overload capacity is sensibly increased.

The author is indebted to Messrs. Brown, Boveri, the makers of the Scherbius phase advancer, for the following examples of the practical results achieved with these machines. In all cases the frequency is 50. The line marked "Recovery" contains the wattless leading kVA by which the lagging kVA of the motor working alone has been reduced. In some cases the reduction is great enough to make the phase angle negative. The slip is that of the motor at full load working alone; this, with phase advancing, is more than doubled. The exact increase can be calculated from the slip-ring voltage, current and recovery.

Scherbius Phase Advancer.

B.H.P. of motor	150	420	500	1 700
Slip-ring volts ..	300	635	770	1 030
Injected volts ..	10·5	21·5	25	14
Slip-ring amperes..	260	380	350	900
kVA of advancer..	4·7	14·2	15·1	22
Original slip, per cent	3	1·6	2·5	1
Original power factor	0·87	0·85	0·78	0·91
Improved power factor	1 —	0·95 Leading	0·995 —	0·965 Leading
Recovery kVA ..	65	290	285	960

Oscillatory Type of Phase Advancer.

The author's phase advancer, more generally known under the name "vibrator," has already been described in his previous paper and the description need therefore not be repeated. It may, however, be of interest to note that its action is simply that of a condenser of very large capacity and that this capacity has a fixed value for every type.* Let m be the mass of the armature reduced to its radius and to mass units of 9·81 kg, ϕ the flux in megalines produced by the external d.c. excitation, and τ the distance between armature conductors in centimetres; then a characteristic constant for any type of vibrator is

$$B = \frac{0 \cdot 1}{m}\left(\frac{\phi}{\tau}\right)^2.$$

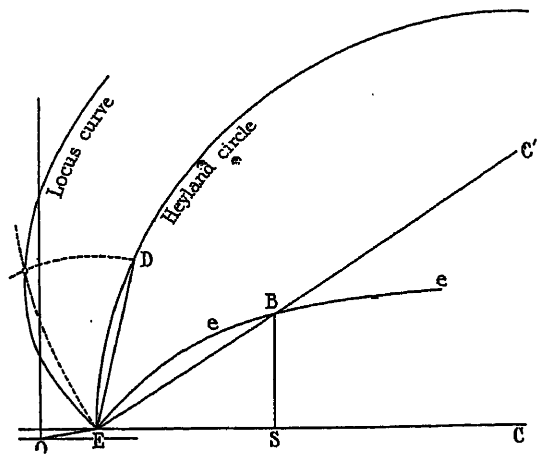


FIG. 13.—Locus curves of induction motor furnished with phase advancer.

* In the following note the expressions differ from those in the text mainly in that they involve M_r, the moment of inertia, and Z_a, the total number of conductors on the armature, instead of the author's m and τ.

The quantity of electricity in a condenser is

$$Q = \int idt = Ce$$

where C is the capacity and e the voltage at the terminals. In the case of the vibrator we have

$$\int Tdt = \frac{M_r\omega}{9 \cdot 81}$$

where T is the torque in kilograms (force) at a metre, M_r is the moment of inertia in kilograms (mass) at a (metre)², and ω is the angular velocity at any instant.

If Z_a is the total number of conductors on a 2-pole vibrator, ϕ the flux per pole in megalines, then the instantaneous watts

$$= ei = i\frac{\omega}{2\pi}Z_a\phi \times 10^{-2} = T \times 9 \cdot 81 \times \omega$$

therefore $$i = T \times \frac{9 \cdot 81 \times 2\pi}{Z_a\phi \times 10^{-2}}$$

also $$\omega = \frac{2\pi e}{Z_a\phi \times 10^{-2}}$$

$$\int idt = \frac{9 \cdot 81 \times 2\pi}{Z_a\phi \times 10^{-2}} \times \int Tdt = \frac{9 \cdot 81 \times 2\pi}{Z_a\phi \times 10^{-2}} \times \frac{M_r\omega}{9 \cdot 81}$$

$$\therefore \quad \int idt = M_r \times \frac{4\pi^2}{Z_a^2\phi^2} \times 10^4 \times e$$

The vibrator therefore behaves electrically as if it had a capacity

$$C = M_r \times \frac{4\pi^2}{Z_a^2\phi^2} \times 10^4 \text{ farads}$$

Referring to the text it will be seen that $\tau = 2\pi r/Z_a$, where r is the radius in centimetres at which the conductors are placed. If now, instead of M_r, we write $\frac{9 \cdot 81\, mr^2}{10^4}$ to bring the expression to the units of the author, we get $C = \frac{m}{0 \cdot 102}\left(\frac{\tau}{\phi}\right)^2$.—M. W.

and the equivalent capacity of a static condenser is

$$C = \frac{1}{B} \text{ farad}$$

From this relation it follows that the leading E.M.F. injected is

$$e = B \frac{I}{\omega_s} \text{volts}$$

where I is the current, and ω_s the circular slip frequency.

Although current and slip are not strictly proportional, both increase together and it follows that, even for light loads, a good power factor can be obtained with an induction motor by adding a vibrator. This is illustrated by Fig. 14 giving the power factor for a 330 b.h.p. motor when working alone and when working with a vibrator. The author is indebted for these curves to the General Electric Co. They refer to a motor supplied to the Sutton Heath and Lea Green Collieries for a line pressure of 6 000 volts, 50 cycles, and a speed of 1 460 r.p.m.

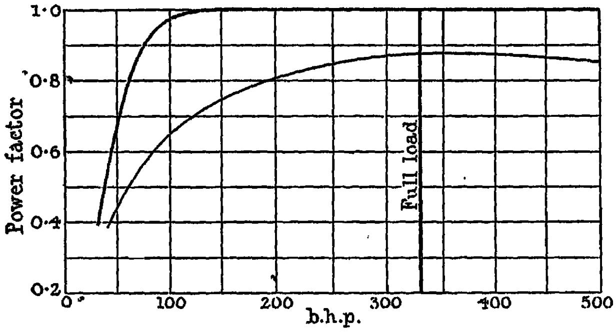


FIG. 14.—Performance curves of a 330 b.h.p. General Electric Co. motor furnished with vibrator.

The loss of power in the armature may be expressed by ρI^2, where ρ represents not only the armature resistance, but also the contact resistance at the brushes and the equivalent values for iron and frictional losses. Let R_2 be the resistance of the rotor phase, then this with the vibrator in circuit is increased to

$$R = R_2 + \rho$$

Since ρ includes iron losses and mechanical friction, both of which depend on the speed, its value is not absolutely constant, though always small in comparison with R_2. The crest value of the speed of the armature lies generally between the limits of 600 and 1 500 r.p.m. Taking some mean value, say 1 200 r.p.m. or 20 revs. per second, we calculate ω as shown below as a first approximation and from this the crest value of the speed. If this comes out different from the first assumption of 20 revs. per second, we determine the new value of ρ and from this the corresponding value of ω in a second approximation. Since the influence of a change in ρ is very slight, this second approximation is generally sufficient. It is not necessary to burden this paper with the complete theory of the vibrator, but some hints as to its practical applications and the method of constructing the locus diagram may be useful. Let, for an induction motor, the Heyland circle, the circle ratio, the working point at full load, the open slip-ring voltage, the rotor current, the phase resistance and the slip be given. The question is what type of vibrator must be used to get approximately unity power factor. To design the vibrator specially for each case so as to get precisely a given power factor, either leading or lagging, is not a good commercial policy. A strongly leading power factor, although it can be obtained by a vibrator, is in any case undesirable because the large increase of rotor copper heat could no longer be compensated by the saving in the stator copper heat, so that the output of the motor would be reduced. Whether the power factor is a few per cent leading or lagging is of little importance; but what is of importance is that by the use of the vibrator a substantial percentage of the full-load kVA shall be recovered in the shape of leading kVA and given to the line. By substantial the author means anything between 40 and 70 per cent. This percentage depends primarily on the original slip and the frequency of the supply; the lower these values are, the greater is the recovery.

Let, in the following, ω_1 be the circular frequency of the line, E the open-circuit phase voltage of the rotor, ω_0 the circular slip frequency when the motor works alone, ω_s the circular slip frequency when the motor works with the vibrator; and let

$$\beta = \frac{\cos \alpha^2,}{\sin \alpha} \text{ where } \tan \alpha = \frac{\text{injected E.M.F.}}{RI}$$

Then the following relations obtain:

Crest value of circumferential force $F = 0 \cdot 14 \frac{\phi}{\tau} I$ kg.

Crest value of circumferential speed $v = \frac{F}{m\omega_s}$ metres per sec.

Circular frequency of slip $\omega_s = \frac{B}{R \tan \alpha}$

Increase of original slip $\frac{\omega_s - \omega_0}{2\pi}$

$$I = \frac{E}{\omega_1} \frac{B}{R^2} \beta$$

The relation between β and $\tan \alpha$ may be taken from Fig. 15.

Having thus obtained $\tan \alpha$ we find ω and the injected E.M.F., $e = \frac{BI}{\omega}$.

The crest value of the armature speed in revs. per sec. is

$$u = v \frac{100}{\pi D}$$

where D, the diameter of the armature, is in centimetres. If this comes out widely different from that at first assumed, ρ must be calculated afresh and the calculation for ω_s, β and $\tan \alpha$ repeated. The correction is generally small. In a rough approximation $\tan \alpha$ may also be taken to represent the ratio $\frac{\text{leading kVA injected}}{\text{kW supplied by line}}$.

But more accurately this ratio is represented by the dotted curve in Fig. 15.

Fig. 16 shows to scale the locus curve for a 12-pole 1 090 b.h.p. motor provided with a 16·5 × 30 cm vibrator; terminal voltage 6 600, frequency 50, open slip-ring voltage 675, normal full-load slip 0·8 per cent. On account of this unusually small slip the power factor is slightly leading above half load, and at full load the recovery is nearly 80 per cent. The motor is direct coupled to a generator which supplies single-phase current to a circuit distinct from the general three-phase circuit.

The data of the vibrator are: Armature 16·5 × 30 cm; commutator 12·5 × 22·5 cm; mass 3·9 kg; flux

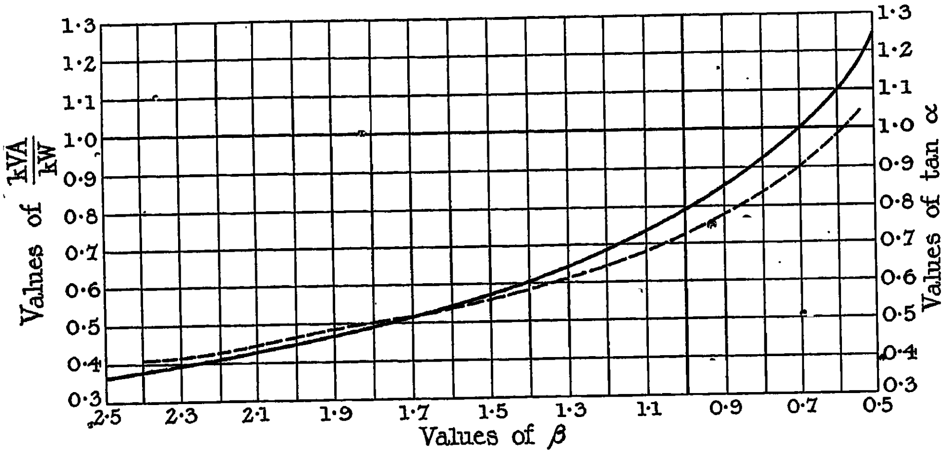


FIG. 15.—Showing the relation between β and tan α in vibrator.

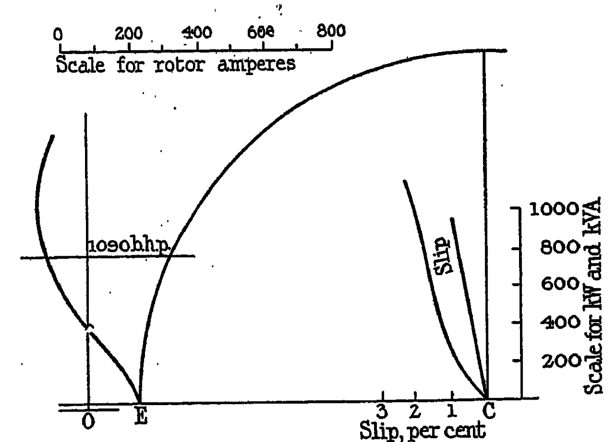


FIG. 16.—Locus curve of a 1 090 b.h.p. motor furnished with vibrator.

4 megalines; $B = 0{\cdot}088$. The equivalent resistance ρ is not constant, but depends on the speed and the rotor current. It is given in the following table:

I =	500	450	400	300	200	100
ρ =	0·006	0·0063	0·0072	0·010	0·0165	0·050
R =	0·0174	0·0177	0·0186	0·0214	0·0279	0·0614

The rapid increase in ρ at very light load is due to certain constant losses such as brush friction, iron losses and the fact that contact losses at the commutator and slip-rings do not follow Ohm's law. The effect on the locus curve is seen in its shape near the origin.

The exciting force is 5 000 ampere-turns for each armature, involving for all three armatures an expenditure of about 600 watts. From the mathematical investigation above cited it will be seen that the phase-advancing effect of the vibrator depends on the square of the flux and is inversely proportional to the mass. This points to the use of 2-pole armatures of small diameter and comparatively great length. The proportion found in practice to be suitable is about 1 to 2. Since the air-gap can be made very small the power required to produce the strong field is not very large; it varies from the smallest type ($D = 10$ cm) to the largest hitherto made ($D = 16{\cdot}5$ cm) between $\frac{1}{2}$ kW. and 1 kW, which means from 0·25 to 0·1 per cent of the power of the motor.

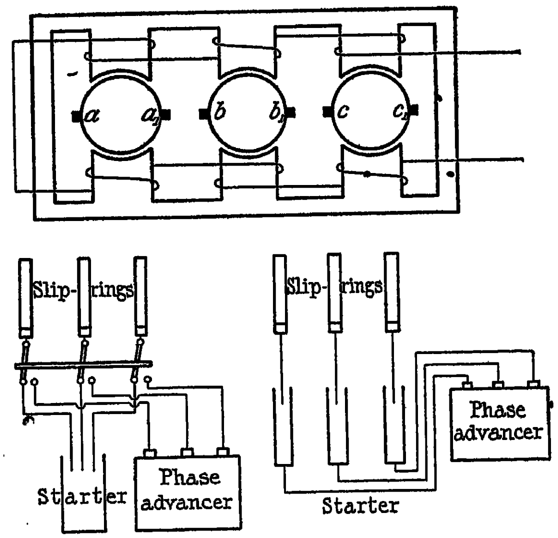


FIG. 17.—Arrangement and connections of Kapp vibrator.

The connection of the vibrator with the slip-rings may be either in star or in delta. The choice depends

on which type comes nearest to the given full-load rotor current, but as a general rule delta connection is preferable because of the smaller current. As the vibrator is essentially a low-voltage machine it is advisable to make it the star point of the rotor circuit. This has the advantage that no switch of any kind is required. The starter must be insulated on all its six poles. On starting, the high-frequency current goes through the vibrator and makes its armatures merely quiver; as the slip frequency decreases they begin to oscillate, and when the starter is completely short-circuited the oscillation has reached the full amplitude. The inductance of the armatures being only a very small fraction of that of the rotor phases there is practically no reduction in starting torque when the vibrator is in circuit. Where the starter is only insulated at three poles a change-over switch must be provided which makes contact with the vibrator before it disconnects the starter.

The housing of the armatures in a common magnet frame and the connections between the phase advancer slip-rings and starter are diagrammatically indicated in Fig. 17. For star coupling the brushes a_1 b_1 c_1 are joined together and the brushes a b c are connected to the slip-rings. For mesh coupling the brushes a_1 and b are connected to slip-ring C; b_1 and c to slip-ring A, and c_1 and a to slip-ring B. If the phase-advancing is only carried to about unity, but does not make ϕ negative, there is no appreciable increase in rotor current, so that there is no increase in rotor copper loss; there is, however, an appreciable reduction in stator current and therefore a saving in stator copper loss. For the same total copper heat the permanent rating of the motor may therefore be slightly increased. Where the rating is fixed with regard to short-time overloads. the increase in rating may be considerable (20 to 30 per cent), so that the cost of a motor with phase advancer will not appreciably exceed that of a larger motor without phase advancer.

The power lost in the phase advancer is very small and is approximately compensated by the saving in stator copper loss, as will be seen from the following figures for which the author is indebted to the General Electric Co.

B.H.P. of motor	350	375	800
Loss in phase advancer including excitation, watts	2 000	3 740	3 900
Saving in primary copper loss, watts	1 900	4 600	4 400

Meters and Tariffs.

More than 10 years ago Professor Arno, of Milan, invented a meter which takes account of power factor in the following way. The meter registers on the same dial two-thirds of the true energy plus one-third of the kVA-hours. This is achieved in a simple and quite inexpensive way by adjusting the angular setting of the pressure coil.*

The values two-thirds and one-third have been arrived at by investigation of the working conditions of a number of Italian supply companies and may, on the whole, have correctly represented the economic conditions of the Italian hydro-electric undertakings. It is, however, not *a priori* certain that it would also be correct for English electricity works. At any rate this system of metering has not found favour in this country. Possibly, also the fact that the consumer could not read off on this meter what was actually the energy for which he had to pay was a drawback. Both these disadvantages have been overcome of late years by a further development of the Arno principle which will be described later.

In this country two methods of charging have been employed. One is known under the name of the "Midland tariff." Under this, the charge for energy consists of two parts, namely, a fixed amount per maximum demand for kVA or current taken at any time during a month or a quarter, plus a flat rate per unit for the energy actually consumed. This requires the provision alongside of the ordinary cosine meter of a maximum-demand indicator which must be so constructed that only a demand sustained over a reasonable time can influence it, as it would clearly be unfair to penalize the consumer for an accidental short-circuit. The advantage of this system is that the consumer can read for himself on the energy meter what amount under the flat rate he will have to pay, and on the maximum demand indicator what the fixed charge per kVA will total up to.

Under the other system, also, two meters are used. One reads true energy, namely

$$\int_0^t \text{kVA} \cos \phi dt = A$$

and the other reads

$$\int_0^t \text{kVA} \sin \phi dt = B$$

From these two readings the average energy factor is found by the equation

$$\cos\phi = \frac{A}{\sqrt{(A^2 + B^2)}}$$

and the charge is made out for a flat rate and for the quantity

$$Q = A\frac{\cos\phi_0}{\cos\phi},$$

which is obviously nothing else than total kVA-hours multiplied by $\cos\phi_0$. Since $\cos\phi_0$, the lowest permissible power factor prescribed by the company, is a constant, the company simply charges at a flat rate for the number of kVA-hours or, if the voltage may be considered constant, for coulombs. In both tariffs the usual coal clause and discount to large consumers can be embodied.

A method not quite as simple as Arno's, inasmuch as it requires two meters instead of one, is in use by some supply companies in France. Arno's meter integrates and shows on one dial two-thirds of the

* *Journal I.E.E.*, 1913, vol. 51, p. 270.

real power and one-third of the kVA-hours. In the French method one meter shows the real energy and the other the reactive energy or $\int$kVA sin ϕdt. The account is made up on a flat rate on the sum of the units registered on the cosine meter plus a certain fraction of the units shown on the sine meter. Here also, as in the case of the Midland tariff, the customer can by inspecting his meters find out for himself not only what is the actual amount of energy he has used, but also what he has to pay for it. The meters are made by the Compagnie pour la Fabrication des Compteurs of Paris in a great variety of types and comprise also a special type, having three dials, for large consumers. On one dial is shown the actual energy, on the other the reactive energy, and on the third the sum of the real and a fraction of the reactive energy. The exact value of this fraction is agreed beforehand between the supply company and the consumer according to the character of his installation, and is provided for by the selection of suitable gearing.

Messrs. Aron Electricity Meter, Ltd., manufacture the Hill-Shotter maximum-demand kVA indicator for use in conjunction with the ordinary cosine meter. Since the plant capacity from the generator to the consumer's terminals is dependent on the current irrespective of pressure and frequency, the instrument is made to register simply the maximum current sustained during a certain time-interval, although the dial is marked in kVA corresponding to the declared pressure. The demand indicator is arranged on the Merz principle, the releasing mechanism being tripped at regular time-intervals by an automatic clock mechanism which is worked by a shunt circuit off the supply leads. The time element is housed in the same case as the meter proper and, since the working agent is merely current, the indication is correct for any frequency.* For balanced loads the instrument may be used in one phase only, but in cases where the supply given to unbalanced loads has to be metered a special three-phase type is made. In such cases the maximum demand does not occur in all phases at the same time, and the sum of these maxima must exceed the true simultaneous maximum. The supply company, however, has to provide plant capacity in each phase corresponding to its individual maximum and not for the simultaneous maximum loading in all the phases combined. If with a balanced load 300 amperes were the combined maximum demand, it would obviously be inadmissible to allow 150 amperes on each of two cables and zero on the third. In such a case of serious unbalancing the use of three maximum-demand indicators is justified. For only moderately unbalanced loads the makers recommend a combined polyphase indicator containing three separate current elements, and this indicator is accurate provided the unbalancing is such that at times of maximum load the current in any one phase does not differ from the mean value of the currents in the other two phases by more than 50 per cent of that mean value.

Messrs. Chamberlain and Hookham, Ltd., have recently developed minimum and maximum energy factor indicators which require no time mechanism. The minimum instrument consists of an ordinary cosine meter and a sine meter having, in addition to the usual pointer, an indicator. The cosine meter has a contact-making device which comes into action after a predetermined amount of energy has passed through the meter. In the sine meter is an electromagnet which, when energized, releases the gear and allows the pointer to return to zero under the action of a spring, the indicator remaining at its then position. Suppose the contact has been set for 10 units. Every time this amount of energy has passed the sine meter returns to zero and, since the lower the energy factor the further will the indicator be pushed, its extreme position corresponds to the minimum energy factor which has occurred during a given period. The dial of the sine meter may be marked either in kVA-hours or directly in cos ϕ. To record the highest energy factor occurring in a given time the contact device is put into the sine meter and the cos ϕ indicator into the cosine meter.

In order to ascertain the general trend in the supply industry as regards discriminative tariffs, the author has made inquiries of some of the larger power companies with the following results. On the whole the importance of framing the tariff so as to induce consumers to take their supply under a good power factor is recognized, but the question is (owing to the unsettled industrial condition) still in a state of flux. Thus one company writes that previous to the war they charged £1 per quarter per kVA of maximum demand plus a flat rate of 0·25d. per unit, but that owing to the increase in prices they had to advance their charges and, everything being so uncertain, they prefer not to state any definite figures.

Another company writes with respect to tariff adjustments according to power factor: "It will be inopportune for you to refer in your paper to the figures we gave you last year, having regard to the possibility of it now being found necessary to amend them."

The engineer of a third undertaking, who wishes to remain anonymous, though he permits the author to mention figures, explains that he uses two cosine meters, one with the pressure phase reversed, so as to get not the sum, but the difference in the two-wattmeter system. From the two readings he finds tan ϕ and from this cos ϕ. The units shown on the true energy meter are increased in the ratio 0·8/cos ϕ, and half this increase is charged in addition to the true units.

South Wales Electrical Power Distribution Co.—This company charges on the basis of the following figures per maximum kVA demand (reduced from true energy by dividing by the energy factor) plus a flat rate of 0·25d. per unit.

For the first 500 maximum hourly units per month, 7s. 6d. each.
For the next 1 500 maximum hourly units per month, 6s. each.
For all further hourly units per month, 5s. each.

It is convenient to put this tariff into mathematical form. Let D be the maximum demand in units, d the flat rate per unit, U the units of true energy con-

* See correction to this sentence in the remarks of Mr. E. W. Hill, page 115.—M. W.

sumed in one month, and $\cos\phi$ the energy factor. Then the monthly charge in pence is:

For D up to 500,

$$\text{Pence} = \frac{1}{\cos\phi}\left\{aD\right\} + dU$$

For D between 500 and 2 000,

$$\text{Pence} = \frac{1}{\cos\phi}\left\{a\,500 + a_1(D - 500)\right\} + dU$$

For D over 2 000,

$$\text{Pence} = \frac{1}{\cos\phi}\left\{a\,500 + a_1\,1\,500 + a_2(D - 2\,000)\right\} + dU$$

$$a = 90,\ a_1 = 72,\ a_2 = 60.$$

The *North Wales Power and Traction Co.* write: "Our standard price at present (March 1922) is £6 per kW of maximum demand plus ¾d. per unit; and in the case of bulk supply we specify in the power agreements that the power factor shall be kept as near unity as possible. With industrial works supply we specify that the power factor shall not be less than 0·85, and secondary equipment is installed to our reasonable satisfaction, so that we can take exception to any plant which gives poor power factor."

The *Yorkshire Electric Power Company* write: "Our tariff for power supply is made up of two parts: (1) A charge per kVA of maximum demand. (2) A charge per unit. This tariff definitely encourages the consumer to have regard to the power factor of his installation, and in a number of cases consumers find it economical to introduce special means for improving the power factor of their installations."

The *Scottish Central Electric Power Company* write: This company has not so far introduced a tariff to induce consumers so to arrange their plant as to provide a good power factor. We have the usual 'Penalty Clause' in respect of low power factor in our agreements for supply, but, owing to the difficulty of enforcing this, it is rarely brought into operation."

The *City of Sheffield* has a tariff * for power based on a fixed charge per maximum demand in kVA and, in addition, a flat rate per unit, with discounts varying according to quantity. The rates originally published in 1913 have now been doubled, and the charges made to large consumers taking a high-tension supply in bulk for any purpose required amount at present (March 1922) to a fixed charge of £8 per annum of maximum demand in kVA and a flat rate of 2d. per unit, less a discount of 75 per cent. The rate is subject to the signing of an agreement embodying a clause adjusting the discount according to the price of coal, also a minimum payment per annum and a term of years.

The *Calcutta Electric Supply Corporation* limits consumers to a power factor of 0·8, and the consumer obtains a bonus if his power factor is better than 0·85. The bonus is in the form of a rebate for each 1 per cent by which the power factor exceeds 85 per cent.

The *Clyde Valley Electric Power Co.* have given the author the following particulars about power factor and tariff, with permission to embody them in this paper: "The mean power factor of our system averages about 0·72 over a week, ranging from about 0·55 to 0·82 daily. We estimate that the increased loss in our 11 000-volt distribution system due to the difference between unity power factor and the power factor obtained is 3½ per cent. The increased loss in transformers and generating plant we put at 0·6 per cent and 0·75 per cent respectively, or a total increased loss of 4·85 per cent. To this must be added the increased steam losses consequent on running additional turbo plant to deal purely with the kVA demand. A further direction in which we estimate that we suffer considerable loss in revenue is the impaired voltage regulation at the customer's terminals due to the lower power factor. The company, therefore, some time ago decided to insert a Power Factor Clause in the standard rates. After careful consideration a 'standard power factor' of 0·8 lag was adopted. The present standard rates are:

"0–250 kW of maximum demand: £10 per annum, plus a running charge of 0·4d. per kWh consumed with coal at 20s. per ton.

"1 000 kW of maximum demand: £8 per annum, plus a running charge of 0·4d. per kWh consumed with coal at 20s. per ton.

"10 000 kW of maximum demand: £6 per annum, plus a running charge of 0·4d. per kWh consumed with coal at 20s. per ton.

"And *pro rata* for intermediate quantities.

"The power-factor rebate is given on the maximum-demand charge, the running charge of 0·4d. being unaffected. With a standard power factor of 0·8 the rebate obtainable with unity power factor is 20 per cent. With a power factor of 0·6 lagging, the penalty becomes 33⅓ per cent, in addition to the maximum-demand charge. In the case of a customer with a maximum demand of 1 000 kW, the rate per kW at unity power factor would be £6 8s.; and with 0·6 lagging power factor it would be £10 13s. 4d., the running charge of 0·4d. per unit being additional in both cases. The rebate is given up to unity power factor, and no allowance is made for power factors on the leading side, these being treated on the same basis as unity power factor. We have given careful consideration to the question of metering the power factor, and the system which we consider introduces fewest difficulties in our Accounts Department is the method of registering the wattless component. The metering of power is accomplished by the three-wattmeter method, and to measure the wattless component only requires the addition of one further wattmeter, which does not in any way interfere with the ordinary metering. We arrange the connections of this wattmeter so that the reading is forward for lagging and the reverse for leading power factor. The wattless component and the kilowatt meters are read at the end of each quarter, and the power factor is determined from the relation of the respective readings. Our Mr. McColl has designed a slide rule with which the power factor can be readily determined by any non-technical person. The method of power-factor

* See correction to this paragraph in the remarks of Mr. S. E. Fedden, page 114.—M. W.

metering which we have adopted gives the consumer the advantage of off-time phase-advancing; that is to say, where static condensers are employed these may be left in circuit continuously, and the wattless component which has been registered on the lag side may be cancelled during off hours by the leading current of the condensers."

The examples of tariffs cited show that the tendency in the supply industry is rather in the direction of a fixed charge for the maximum demand, augmented by a flat rate per unit, than only a flat rate adjusted according to power factor. The latter is unscientific and can, under circumstances, be unfair to either the consumer or the company, as can easily be seen if we consider two cases which may well arise in practice.

Assume that a consumer installs only synchronous induction motors. His power factor will always be leading, and on a flat rate based on and proportional to $\cos \phi_0/\cos \phi$ he will always pay too much. Yet as long as his neighbours have a lagging power factor he is benefiting the supply company. Only in the unlikely case that all consumers were to use the whole supply to work phase-advancing motors would the company also be injuriously affected.

On the other hand, a consumer may use ordinary motors and correct the general power factor of his whole installation by static condensers. With a load factor of 0·83 he will consume, every working day of 8 hours, 660 units for every 100 kW of his peak load. Under a tariff which allows him an energy factor of 0·85 without penalty he will be able to make the necessary correction by installing condensers, but he will not install more than are absolutely necessary. His mean load is 0·83 of the peak load, and his power factor at peak load may be as low as 0·7. Taking this as a reasonable figure, we find that at peak time his condensers will have to inject 39 kVA for every 100 kW of peak load. If he leaves the condensers in circuit for 24 hours a day he can reduce their capacity to one-third and yet keep within the permissible power factor of 0·85. But at peak time his power factor will be only 0·78, and as the intention of the tariff is to make the consumer pay his fair share of the additional current load on the plant at peak time, he ought to pay $0{\cdot}85/0{\cdot}78 = 1{\cdot}11$ times the minimum rate. Actually he only pays the minimum rate. The company receives 11 per cent less than corresponds to the intention of the tariff.

Such anomalies cannot occur under a maximum-demand tariff. The consumer may leave his condensers in circuit permanently without depriving the company of a certain percentage of the revenue to which they are entitled, because the fixed charge is not influenced, or is only slightly influenced, by energy factor. For the same reason the consumer cannot be penalized for doing a little more phase-advancing than is necessary. The basic idea of the two-part tariff is that the fixed charge for maximum demand should recompense the company for capital outlay incurred on account of each consumer, whilst the flat rate per unit should recompense them for running costs. If the voltage at consumers' terminals is kept constant, the maximum kVA demand can be found from a maximum-current indicator scaled in kVA. Under these conditions the metering becomes a very simple matter. All that is wanted is a coulomb meter combined with a time element which brings the pointer back at regular intervals of 10 or 20 minutes, leaving the indicator in its farthest position, and an ordinary cosine energy meter. Neither energy factor nor power factor enter in the making up of the total charge, and the customer can by inspection of the two meters find out for himself what energy he has used during a month or a quarter and how much he has to pay for it. This is an advantage, especially with small consumers, who cannot be expected to understand the mathematics of power and energy factor.

The condition of constant terminal voltage may not, however, be strictly maintained. If the voltage is higher than the declared voltage on which the maximum demand indicator is scaled, the number of kVA read off the indicator, and also the fixed charge, will be too low, to the detriment of the supply company. If the terminal voltage decreases, the indicator will show too large a value for the maximum kVA, to the detriment of the consumer. The greatest voltage-drop occurs at peak time and, generally speaking, this is the time when consumers individually have their own peak demand. The result is that the fixed charge will be in excess of that for the true maximum kVA demand in the same percentage as the actual voltage falls short of the declared voltage.

The error thus introduced by excessive voltage-drop may be appreciable and, as it is always against the consumer, we find that most supply companies do not use the simple (coulombs)/(time) indicator, but replace it by a (units)/(time) indicator, and translate the reading into maximum kVA demand with reference to the energy factor by dividing the number of units by $\cos \phi$. Under this more accurate system of metering three instruments are required; (1) A maximum-demand kW indicator which is a cosine meter with a time element; (2) an ordinary cosine energy meter; and (3) a sine meter to record $\int EI \sin \phi dt$. From the two last-named instruments is found $\tan \phi$, and from this $\cos \phi$.

If P_0 = maximum kW demand,
P = maximum kVA demand,
m = charge per maximum kVA demand,
U = number of units consumed,
d = flat rate, then

$$P = \frac{P_0}{\cos \phi}; \text{ and the total charge} = mP + dU$$

Under this tariff there is no necessity to place the consumer under any restriction as to a minimum power factor. The latter may be as bad as suits the consumer's method of working his machinery, because its effect will make itself felt in the energy factor and thus appropriately increase the fixed charge, thereby recompensing the supply company for their greater expenditure on electrical plant.

In conclusion the author thanks the various firms and engineers of power supply undertakings for the information which they have kindly supplied to enable him to present this paper.

Discussion before The Institution, 16 November, 1922.

Mr. Ll. B. Atkinson: The circumstances in which this paper is read to-night are most unusual. The paper was presented to the Institution in April of the present year, and four months later the author had died. We are deeply indebted to Prof. Miles Walker for having carried the work to a point which has permitted the reading of the paper to-night. Gisbert Kapp was one of my earliest and most intimate friends in the electrical world. The last time I saw him was during my tenure of office as President of the Institution, when I spent a night with him at his home at Birmingham. We had been to an Institution meeting, and, when we got home, his family and household had retired to bed. He said to me: "Atkinson, we must have a night like we used to do, and a long discussion." It was then about half-past ten. The discussion continued until between two and three in the morning, just as in the days when we were young men we would spend half the night discussing many of the difficult problems which confronted us in those days. To me, and I am sure to him also, it was a great delight thus to revive a form of entertainment and instruction in which we had so often taken part in our young days. I realized at that time that he was failing physically very fast, but he was mentally—as this paper shows—as alert as ever. It is difficult for me—and there are one or two members present who will recollect those early times—to realize how, when Kapp began his work on the dynamo and other electrical subjects, he and all of us were groping in the dark. I saw, in those evenings I spent with him, how step by step he was coming to the idea of the magnetic circuit, which finally unlocked so much. I believe the brothers Hopkinson published the same idea before he did, though not in the same terms, but nevertheless Kapp was working on the idea before anyone else in the electrical world had got a grip of the fact that we could use the idea of a circuit for magnetic actions in the same way as we had been accustomed to use the idea of an electrical circuit. That method, in fact, was a revolution. After that Kapp went on, always as a leader—at one time he was our President—and as a teacher. The transmission of power, alternating currents and many other matters in turn claimed his attention, always with some new illumination which he communicated to others freely, in teaching, in papers and in books, and now to-night, after he has gone, we still hear his voice and sit once more as learners at his feet.

Dr. S. P. Smith: The paper brings out to a certain extent the point that power factor improvement is not merely an economic question at the present time, but is becoming a question of necessity on certain systems in order to obtain a good voltage regulation. The question of the particular apparatus which ought to be used is, of course, no new one. We are greatly indebted to Dr. Kapp, however, for giving us such a valuable criticism of all the useful methods that are known at the present time. In this connection I should like to refer to two papers * published in 1909. It is interesting to note that Prof. Miles Walker, who has been so good as to revise Dr. Kapp's paper, was also a pioneer in this matter. In Mr. Mordey's paper, the conclusion arrived at in comparing static with rotary condensers at that time would seem to be confirmed to a large extent by the present paper; both as regards capital cost and running cost, Mr. Mordey found that the rotary was more expensive than the static condenser. It is well known that in many systems the static condenser is being used as a protective device, and it may well be that in some installations the static condenser can be used to serve both for protection and for improving the power factor, though the possible injurious effect of capacity where there are voltage ripples must not be ignored. One point in connection with the syn-

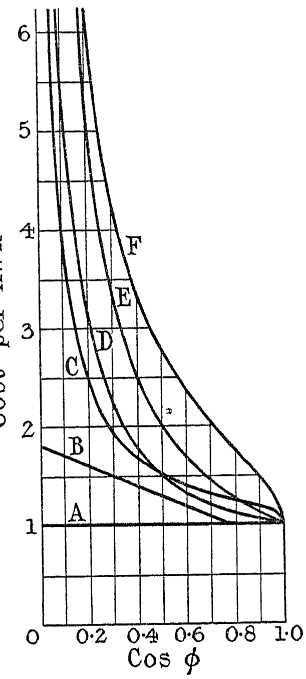


Fig. A.

chronous induction motor came out in a discussion which I had with Dr. Kapp, i.e. its low overload capacity. The synchronous induction motor is a compromise, the synchronous motor being a machine with small armature reaction, and the induction motor a machine with large armature reaction; combining the two results in a small overload capacity, which may be troublesome in some cases and need special design to overcome it. In conclusion, I should like to refer to the final part of the paper, dealing with tariffs. The author has given us several methods of charging.

* W. M. Mordey: "Some Tests and Uses of Condensers," *Journal I.E.E.*, 1909, vol. 43, p. 318.
M. Walker: "The Improvement of Power Factor in Alternating-current Systems, *ibid.*, vol. 42, p. 599.

Fig. A is taken from a publication of the Swiss Electrotechnical Institution, and shows at a glance the effect of different methods of charging.

Let power component $\int VI \cos \phi \, dt = X$,
reactive component $\int VI \sin \phi \, dt = Y$,
total kVA-hours $\int VI \, dt = Z$.

Then curve A = charge according to X,
C = charge according to $X + 0\cdot3Y$,
D = charge according to $0\cdot5X + 0\cdot5Z$,
E = charge according to Z,
F = charge according to $X + Y$.

In general, the charge may be proportional to $(1 - a) X + aZ$, since the generating cost depends on X, and the transformation and distribution costs are proportional to Z. Curve E thus represents the case when the generating costs are negligible compared with the transformation and distribution costs, while curve A represents the case where the only important cost is that of generation. The value of a must obviously be adjusted to suit given conditions. In hydro-electric work a would obviously be very different from its value with a steam generating station. Curve B shows how the cost can be increased by 1 per cent for each 1 per cent reduction in power factor below 0·8.

Mr. K. Edgcumbe: On the last page of the paper the author gives it as his opinion that the correct charge is an amount per kilowatt-hour plus a fixed charge depending on the maximum demand, and he lays it down that this fixed charge should recompense the company for the capital outlay incurred on account of that consumer. This, I think, is the aim of every supply undertaking. He goes on to point out that if the voltage can be regarded as constant, all that is necessary is a coulomb meter combined with a time element or, in other words, an ammeter with a maximum-demand pointer, and that is undoubtedly the simplest method. The author, however, qualifies that statement by adding that the condition of constant terminal voltage may not always be fulfilled. But I am inclined to think that the alternative given by the author is subject to another objection almost as strong and, apart from this, it is complicated, entailing three instruments: the ordinary cosine (energy) meter, a maximum-demand indicator and a sine meter. By taking the readings of the sine meter and the energy meter, and dividing one by the other, the tangent of the angle can be found; from that, in turn, the angle and hence the power factor can be calculated and the kilowatts may be read from the maximum-demand indicator. By dividing the one by the other, the maximum demand in kVA is obtained. Now this appears to me to be a very elaborate way of arriving at the result, and it is subject to the objection that the power factor measured is the *average* power factor for the quarter. I do not think that one is justified in assuming that it was the consumer's power factor at the time he was taking his maximum demand. Comparing the two systems, therefore: in the one case there is the possibility of the voltage varying (in favour of either the consumer or the supply company), and in the other case there is the certainty that the power factor assumed is not the power factor at the time of the consumer's maximum demand. Of the two alternatives I prefer the former. The strong point in favour of that method is that it embodies a maximum-demand ammeter which is at all times easily seen by the consumer; whereas in the other case he cannot tell until the end of the quarter what his maximum demand has been, and then it has to be multiplied by a constant, the object of which is difficult to explain, and the method of arriving at which is complicated.

Mr. W. E. Rogers: When one first studies the power-factor-improvement problem, everything seems to point towards the employment of static condensers, until one realizes that the voltage question has an important bearing on the matter, and that unless about 600 volts can be applied to the condensers they will not be a practical commercial proposition. Moreover, the question of master patents arises. I should like to have some information in regard to the power factor of a.c. electric arc furnaces, and a.c. electric arc welding processes, etc. With ammeter, wattmeter and voltmeter readings a power factor of the order of 0·4 or 0·5 is indicated. It seems to me that there is a total absence of current during a certain portion of a cycle, and there is therefore no wattless current to correct. How is that power factor produced (if it is a power factor), and how is it to be improved? Would not "equivalent power factor" be a more appropriate expression?

Mr. E. T. Williams: I had occasion to consider this subject recently in connection with a works where the power factor was gradually becoming worse. The old agreement with the supply company was on the kilowatt basis; the main was being overloaded and there were voltage troubles. We therefore had to face the problem, particularly as the supply company in their new agreement were charging on the kilovolt-ampere basis. After considering the various methods of dealing with the problem we installed a static condenser and, after testing it, found it to be a commercial proposition. From that time until the present we have not had the slightest trouble with it. I cannot but feel that all old agreements made on a kilowatt basis should be replaced, as they expire, by new agreements on a kilovolt-ampere basis. I also feel that in many cases where extensions or enlargements of mains appear to be required, the trouble might be overcome by providing some type of phase advancer. The great advantage of the static condenser is that one merely has to put it into position; it requires no attention, and is advantageous from the points of view of both the consumer and the supply company.

Mr. W. B. Woodhouse: I think it is some 18 years since I first adopted a method of charging based on kilovolt-amperes, with the object of dealing with this question of idle current. The paper gives us some idea of the relative merits of the different means of correction, but the problem we have to face in practice is: Who shall do the correction, the supply undertaking or the consumer? Of course, if supply engineers could design all the installations, then motors would be

O. Ganguillet: *Schweizerischer Elektrotechnischer Verein Bulletin*, 1921, vol. 12, p. 406.

obtained with less magnetizing current than most of them now require, and we could in every way reduce the amount of idle current on the system. As that is not possible, the user has to be encouraged to improve his power factor by a tariff. I do not think it is really necessary for that tariff to follow the cost line too precisely. A consumer should be prohibited from having a power factor of the order of 0·5 or 0·6. That can be done by imposing regulations, but it should be made prohibitive in price for anybody to have an installation with so low a power factor. That can be effected by a fairly high kVA charge. I have dealt with a number of cases where the consumer has corrected the power factor and reduced the demand very substantially. I have found synchronous motors very convenient for a number of purposes where there is continuously-running machinery. I installed one 10 years ago which is still running, and which has an automatic pressure regulator. This regulator is actually designed to regulate the pressure, but it also regulates the power factor. I believe that the installation of that particular machine, as compared with an induction motor, saves the consumer something like £2 000 a year. In another case, a very large installation—one of those difficult installations in which there is a large number of heavy motors to meet peak conditions—was working with a power factor of something like 0·5. That has been corrected by means of static condensers, with the result that the bill for current has been reduced by about £8 000 a year.

Mr. C. L. Lipman: I agree with the author that a fair way of charging for electricity consumed, from both the consumer's and the supply company's point of view, is to have a fixed charge for the maximum demand, augmented by a flat rate per unit. In the last chapter the author repeatedly refers to the integrating wattmeter or watt-hour meter as the "cosine meter." This name may be justified from the time-integral point of view, but is objectionable for other reasons. On the Continent by a "cosine meter" is usually meant a power factor meter and not an energy meter. It is further surprising that in a paper dealing with the "Improvement of Power Factor" no mention is made of power factor indicators. Wherever power factor regulation is attempted a direct-reading power factor meter is necessary, as it is out of the question to calculate the power factor from the readings of wattmeters, voltmeters and ammeters. It is a well-known fact, and reference to Figs. 7 and 9*b* of the paper will confirm it, that in the case of synchronous machinery the power factor varies with the load on the machine. It is therefore of extreme importance to employ such a power factor meter as would indicate the exact power factor or phase angle between the current and the electromotive force, independent of the magnitude of these quantities. Such an improved power factor meter has recently been developed by the speaker, and possesses many novel and unique features. It works on the principle of the "component fields," according to which the electromagnetic forces acting upon the moving-iron system are produced by field coils having their axes parallel to each other in separate parallel planes, the moving element comprising a spindle (made up of one or more co-axial magnetic systems, which are being magnetized by individual pressure coils) and an appropriate number of thin iron vanes mounted thereon in these parallel planes. The vanes are specially shaped, and their axes of symmetry are set so as to correspond to the time-electrical displacement (expressed in degrees of phase angle) of the currents in the various phases of the system on which the instrument is to be used, i.e. 90° and 120° for two- and three-phase circuits, respectively. The distinguishing feature of these phase meters is that, owing to their special construction, no resultant rotating field is set up, and consequently no "rotational drag torque" upon the moving-iron system is produced, and the disadvantages arising from that torque are eliminated. The magnetic fluxes due to the current coils always oscillate to and fro periodically in parallel planes. The fluxes due to the pressure coils oscillate periodically up and down co-axially, thereby magnetizing the corresponding iron vanes of the independent, but component, magnetic portions of the moving systems, these portions being magnetically separated by non-magnetic material. The turning moment on the moving system is therefore developed by virtue of the fact that a number of directive pulsating magnetic forces, due to the field coils, are regularly applied to the vanes magnetized periodically and in correct sequence by the pressure coils, which vanes may be regarded as magnetic levers mechanically displaced relatively to each other. The combined electromagnetic effect is such that for any given power factor the moving system is in neutral equilibrium, and thus it is independent of the magnitude of the load. If the phase angle between the current and potential difference of the mains alters by a given amount, the moving system will shift by an equal amount, and will again take up a definite and stable position corresponding to the new conditions. The position of the pointer therefore indicates the phase angle. For convenience, however, the scale is graduated in values of the power factor.

Mr. W. M. Selvey: I should like to separate, to some extent, technical questions from the question as it appears to consumers. It is undoubtedly a fact, from the technical point of view, that the magnetizing current should be provided at the place where it is wanted, and that it should not be transmitted by the supply undertaking. Hence we are now adopting the practice of using a sine meter at a consumer's terminals for integrating the total amount of magnetization. For a number of years I have been using cosine meters reversed as sine meters for the accurate determination of power factor on steady load. In connection with a commerical load, however, the matter must be regarded from a rather different aspect. There are two separate factors to be considered, the capital expenditure on mains and generating plant, and voltage regulation. The sine meter measures or adds up wattless units or, as Mr. Woodhouse called it, idle current. Thus it may be used to measure the magnetizing kVA taken by all the motors over the whole system. It cannot be applied, for instance, to show the power factor at the time of maximum demand, for a very much lower

figure will be indicated as the average power factor. The maximum-demand indicator measures only the power factor at the period of highest load, and therefore deals with the capital charges part, which the sine meter does not. Either of these methods separately, therefore, would not sufficiently disclose to us the relative cost of giving a supply to any particular consumer; we want both of them. Surely that is the only reason for studying the subject. We make the supply as cheap as we can and, as far as tariff is concerned, we try to be fair as between one consumer and another; and all metering is dictated by this desire. It is very difficult to explain to the non-technical customer what power factor really is, and why he should be charged more or charged less under different circumstances. It is undesirable to lay too great stress upon it unless the supply undertaking is so well convinced of the value of any improvement to them that it is prepared to give a rebate on the price. In doing that, they are trying to be as fair as possible to the consumer who is prepared to help them to cheapen the supply. The other point of view, which has been voiced by Mr. Woodhouse, is also in my opinion correct in the sense that, if a consumer has a really bad power factor, I think one is entitled to say to him: "You are abusing your privileges, and we shall simply not allow it at any price." In some such cases where I have had to act for the consumer and advise him as to the way in which he should satisfy the requirements of the supply undertaking, I have told him frankly: "I cannot contend on your behalf that running with a very low power factor is fair to the supply undertaking or to the other consumers." He has been impressed by this argument and I have had no difficulty at all in converting, with the help of the manufacturers, large induction motors running at a very bad power factor into synchronous motors by the injection of direct current into the rotor. I think that is the best way of dealing with the problem, but I rather deprecate any very strong pressure being put on individual consumers, because we are only now gradually developing these synchronous motors to any large extent. In this connection perhaps it would be interesting if Prof. Miles Walker would consider a small point which is not quite clear to me at present. Take one of these motors having a synchronous stalling torque somewhere about full load. There is a certain point, subject to the amount of excitation used and to the air-gap, where it is unstable. Electrical and mechanical engineers sometimes have to use a reciprocating machine where, under certain conditions, there is a very large cyclic irregularity. What will happen if we put two or three of these motors in parallel under conditions of considerable cyclic irregularity, where the load on each is constantly liable to be on the unstable part of the curve?

Mr. W. E. M. Ayres: There is one matter which I know the author intended to add to the paper, i.e. the possibility of improving the power factor by re-grouping the motors. There has been much discussion in the United States on power factor improvement, and in these discussions the re-grouping of motors is always given as the first method of tackling the problem. Of course, that cannot always be done; there are certain circumstances in which individual drive is absolutely essential. Unfortunately, in many of these cases of individual drive there is bound to be a very low load factor, e.g. rubber works, bleaching works, etc. At the same time, a very great improvement may be effected by the re-grouping of motors. I think that is one of the reasons why the individual driving of looms in textile mills is not so popular as it once promised to be; the little motors employed must have an extremely high starting torque and even at full load a power factor of only 0·77 or 0·78, but running, as they normally do, at ⅝ full load, the power factor is reduced to 0·6. By driving the looms in groups or rows, with underground high-speed shafting running in roller bearings and with upward driving—which is quite easy to arrange—all the advantages of individual drive can be obtained, but the diversity factor will correct that difference in output required between normal load and working load, and the power factor will be greatly improved. There is little doubt that in the future very large extensions of industrial load will be employed, and the proper utilization of synchronous motors will ensure a reasonable power factor under such conditions. At the same time, there will be trouble in an industrial district like Birmingham where there are hundreds of small works using only one or two motors of 5, 10 or 15 h.p., probably running at about half load; it is a problem for the supply undertaking to know what to do under such conditions. One cannot insist on all these consumers putting static condensers on their motors. At the same time, the increased bulk supply will very largely correct the power factor on the feeders. I have had a good deal of experience of the induction-type synchronous motor, which seems to have given excellent results. The experimental work in connection with them was done a long time ago; I believe Danielson's patents date back to 1900. It is only during the past few years, however, that they have come into their own. They are now being widely adopted, and, although they have been criticized, I believe they have never been actually condemned. Although it does not refer to the motors made by the firm with which I am connected, the point has been raised as to whether a certain amount of trouble is not experienced with the exciter drives on these motors. With the salient-pole type of synchronous motor the field winding is screened by the damping winding in the pole-shoes, but with the induction-type synchronous motor the field winding is not screened. Any pole-swinging due to a change of load will cause circulating currents which, in the induction-type synchronous motor, must pass through the exciter, thus creating very large torques in the exciter. Those torques, in extreme cases, might amount to as much as 10 times the normal exciter torque. I believe that in some cases trouble has resulted because that point has been completely overlooked.

(*Communicated*): Much has been made of the small overload capacity of the induction-type synchronous motor, and I am glad to see that the author elaborates my remarks in the discussion of Mr. Carr's paper * by his Figs. 2 and 3. It is a rule, in well-designed

* *Journal I.E.E.*, 1922, vol. 60, p. 165.

motors of this type, to give 75 to 100 per cent overload capacity, and, according to my experience, greater overloads are usually looked after by the circuit breaker. I do not consider that the synchronous motor and the motor with phase advancer are really competitive alternatives. Each has its own sphere of utility and its own limitations. It is not economical to correct power factor much beyond unity with phase advancers, not only on account of the rotor heating, but chiefly on account of the disproportionate increase in size of the phase advancer itself. On the other hand, it is very economical to do quite a large amount of phase correction by means of a few over-excited synchronous motors working at, say, 0·80 leading power factor. For single large motors and where leading kVA at light loads is not required, the phase advancer will score. Where the motor to be corrected is subjected to very heavy overloads, the phase advancer will also prove superior. On the other hand, with a miscellaneous system it is cheaper and more economical to make one or two of the large motors of the synchronous type with leading power factor and constant excitation at all loads. The increased slip when phase advancers are used must not be forgotten if the motors are for driving fans or centrifugal pumps, as these machines are very sensitive to speed variation. Also, the fact should be kept in mind that with induction motors the overload capacity is reduced in proportion to the square of the voltage, whereas with synchronous motors it is reduced in direct proportion only. This may be of considerable importance on some systems with widely varying voltage.* There is no appreciable difference in either efficiency or cost between the two methods of power factor correction, and the lower economic limit in each case seems to be for units of 120 to 150 h.p. Attempts have been made to utilize electrolytic capacity in the rotor circuit of induction motors as a phase advancer, but so far this is in an experimental stage, and for scattered systems of small motors there appears to be no alternative to the static condenser at the present time.

Professor W. Cramp (*communicated*): It seems to me very fitting that I should take this opportunity of communicating to the Institution the results of experiments suggested by the late Dr. Kapp, and arising out of his discussion on the paper * by Mr. Carr. Dr. Kapp, at the time of his remarks, declared that if he had been still at the University of Birmingham, he would have made these experiments, so I at once undertook to get them done. They were carried out very satisfactorily by Messrs. Elliott and Francis, who were fourth-year students at the time and are Students of the Institution. In his calculation of the torque at which a synchronous induction motor will synchronize, Mr. Carr omitted the effect of putting the exciter reactance into the rotor circuit. Dr. Kapp insisted that this would materially affect the induction motor torque, and the result proved that he was quite right. For this purpose a Siemens standard three-phase induction motor with a slip-ring rotor was tested with various additional reactances put in the rotor circuit. The ratio of the added reactances to the original rotor reactance varied in the tests from 0 to 8. But, as it was estimated that the ordinary exciter armature would only make this ratio about 0·5, I shall quote the results corresponding as nearly as possible to that figure, namely, to 0·439. The comparison is then as follows: With no additional reactance and a stator current of 34 amperes, which corresponds approximately to full load for the machine, the torque was 64 pound-feet and the output 7·4 kW. With the reactance inserted, and practically the same stator current, the torque was reduced to 57 pound-feet and the output to 6·8 kW. This result will sensibly modify the figures given by Mr. Carr, and also Dr. Kapp's own circle diagrams; and when the switching arrangements are such as to insert the exciter armature at the time of synchronizing, it will render of doubtful value the theoretical calculations put forward by the former. Complete curves were taken over the whole range of output for the motor, but the important result is that corresponding to full load for which the figures are given above.

Mr. E. W. Dorey (*communicated*): The static condenser for the improvement of power factor has been adversely criticized by Mr. Rogers on the score that its cost renders it an unsound commercial investment. This statement must have been made without a knowledge of facts, as I have connected on behalf of the manufacturers with whom I am associated numerous installations of static condensers which give the consumer a return varying from 50 to 80 per cent and more per annum on capital outlay, and surely this is a sufficiently sound investment. The static condenser can be connected to a circuit and for all practical purposes forgotten, as it needs no attention, has a high efficiency—not less than 99·5 per cent—has proved itself to be a thoroughly sound investment for the correction of power factor of both individual motors and motors in bulk, and merits the closest consideration on the part of all engineers interested in the improvement of power factor. A static condenser connected direct across the stator terminals of an ordinary induction motor, of either the slip-ring or squirrel-cage type, and switched on or off with the motor, provides a very straightforward and satisfactory means of improving the power factor of an individual motor. According to Dr. Kapp, the synchronous induction motor costs about 20 per cent more than the induction motor of the slip-ring type, and this difference in cost, together with the better efficiency of the induction motor, will in the majority of cases be almost sufficient to pay for the static condenser. An induction motor combined with static condenser would give all the advantages of the induction machine and none of the disadvantages of the synchronous induction motor, as with the latter the synchronous stalling torque is a serious drawback and it is impossible to short-circuit the slip-rings. There is also the maintenance and attendance on the exciter to be considered, and, generally, the synchronous induction motor is a more complicated machine. Dealing with the question of tariffs, it is now becoming generally recognized that a penalty for low power factor is a necessity if

* "Induction-type Synchronous Motors," *Journal I.E.E.*, 1922, vol. 60, p. 165.

the supply undertakings are to have any hold on the consumer. I know of large supply undertakings operating to-day with a power factor of 60 to 70 per cent and they are quite helpless in the matter, as their standard rates do not penalize the consumer for low power factor. If the consumer is penalized for low power factor, the problem resolves itself into a pecuniary one, and the manufacturers of synchronous plant, condensers, etc., may be safely relied upon to solve all the low power-factor problems to the advantage both of consumers and the supply undertaking. Rules and regulations enforcing a limit of power factor cannot be expected to provide a satisfactory solution, as the consumer must be induced and not driven to improve the power factor. The two-part tariff, a fixed charge per kVA per quarter or per annum, with a running charge per unit, has proved to be a sound tariff on several large supply undertakings known to me personally, but the development of this form of tariff is being retarded owing to the difficulty in getting a really sound metering equipment which is not too expensive. For small loads a popular combination is a Reason electrolytic demand indicator and a unit meter, and for larger loads the Hill-Shotter meter referred to by the author gives reasonably satisfactory results, but what is badly needed is a meter which will accurately record the kVA average demand over a time period and over a reasonable range of power factor. I understand that one meter maker at least is busily engaged on the solution of this problem, and there is certainly ample scope for development in this direction. I am not in favour of a combination of cosine meter and sine meter, as with this metering equipment the supply undertaking plays into the hands of the consumer, who might have a static condenser installed, and by connecting it in circuit during no-load hours would reverse the sine meter and so give an entirely fictitious average power factor, which might in fact give a result showing a leading power factor when actually the power factor at time of maximum load was lagging to the extent of 60 per cent or even worse. It appears to me that the chief concern of the supply undertaking should be to ascertain the power factor at time of peak load, i.e. the maximum demand in kVA, and this brings one back to the two-part charge referred to above. As far as electricity supply undertakings are concerned, no rapid development in the employment of apparatus for the improvement of power factor is likely to take place until a penalty for low power factor becomes general, and then some real progress will be made. The application of a two-part tariff of kVA demand and running charge has gone far beyond the experimental stage, and has been proved by many supply undertakings to be a thoroughly sound commercial tariff and one which tends to reduce the average price per unit sold to a minimum by the more efficient utilization of capital expenditure on all plant rated in kVA, such as alternators, cables, transformers, etc., and a decrease in generation and transmission losses.

Mr. S. E. Fedden (*communicated*): The subject of power factor and its correction becomes increasingly important to both supplier and consumer, and any suggestion which will fairly distribute the burden of rectification as between the interested parties must receive the utmost consideration. The causes, effects and rectification of low power factors are exhaustively dealt with in the earlier portion of the paper, and our thanks are due to the author for so lucid an explanation of the methods which may be adopted either to neutralize entirely or, at any rate, minimize the effects of the inherent difficulties. Obviously the particular method of rectification will depend on the individual circumstances connected with each installation, and all appear to have advantages in certain particular instances. I am particularly interested in the section dealing with meters and tariffs. I am not impressed by the Arno method, as it is not a true indicator of any factor connected with the supply. The introduction of the Merz principle in the measurement of kVA by the Hill-Shotter demand indicator is a step forward, but this instrument relies upon a constant voltage for its accuracy. However, I think it is to be preferred to a thermal indicator, to which we have hitherto been restricted when requiring to measure kVA. The examples of the various tariffs in force are extremely interesting, but I should like to make a slight correction in the tariff quoted as in operation at Sheffield. At the time the details were gathered, the increase was 100 per cent on the ordinary flat rate, but such increase did not necessarily apply to the maximum-demand rate, the basis of which is £4 per annum per kVA of maximum demand, plus ¼d. per unit, subject to a coal clause. The confusion is caused by the fact that at one period during the war the maximum-demand consumer was given the option of being charged either according to the coal clause or in accordance with the authorized general percentage increase on the price list. While the price of coal was exceptionally high during the coal strike, the former option was exercised, but when prices for coal fell, the usual rate was restored. Perhaps the most interesting tariff quoted in the paper is that of the Clyde Valley Company, which embodies many novel features. The reasons underlying the differential charge per kVA for varying demands is not apparent, but the adoption of a standard power factor, with rebates or penalties for any variation, appeals to me as being a fair arrangement between consumer and undertaker. I also agree with the limitation of the rebate to power factors up to unity, as of course it is possible for a leading power factor to be as objectionable as a lagging power factor. In the paper it is suggested that four wattmeters are used to record the various measurements, but it appears to me that two instruments only are required, viz. a three-phase cosine meter with maximum-demand attachment and a sine meter to determine the wattless component. Personally, for my own undertaking, with comparatively short transmission lines, I cannot see my way to allow the penalties incurred during the ordinary working hours (when power factor rectification is most advantageous) to be cancelled during "off" hours by leaving condensers continuously in circuit. The objection would particularly apply to week-ends, when the leading component could not be economically or usefully applied. The author goes on to show how this method of charging might result in penalizing the undertaking. In Sheffield

the system adopted is to measure the maximum kVA on a thermal indicator, and the power by the ordinary cosine meter. We recognize the possible error due to excessive voltage-drop, and have under consideration the substitution of the method described by the author in the last paragraphs of the paper. From the commercial point of view, the rectification of power factor by the consumer will repay the capital expenditure in about 2 years when the demand charge is £4 per kVA and the cost of static condensers is in the neighbourhood of £5 to £6 per kVA.

Mr. E. W. Hill (*communicated*): A slight error appears in the reference to the Hill-Shotter maximum-demand kVA indicator in the section of the paper headed "Meters and Tariffs," where it is stated that the "indication is correct for any frequency." In point of fact, although moderate variations of frequency from the declared value, such as might be expected in practice in a supply system, do not affect the accuracy of this instrument, which is self-compensating for such variations, yet the instrument would require separate calibrations for two frequencies differing widely, e.g. 25 and 50 periods. It is probable that the sentence was intended to read "and since the working agent is merely current, the indication is correct for any *power factor*," which is a correct statement of fact. A very interesting description follows of Messrs. Chamberlain and Hookham's arrangement of energy factor indicators. The arrangement as described, however, invites criticism on one or two points. First, as regards the operation of the instruments arranged to indicate the maximum energy factor, when this factor (I prefer to adopt the more usual term "power factor") has a value in the neighbourhood of unity, the sine meter (which has then the contact-making device for operating the non-return pointer on the cosine meter) will register very slowly, and indeed should not register at all at unity power factor. In this instance the consequence will be that the contact-making device will not operate, and the cosine meter's pointer will be pushed on and on without ever being released, no definite indication will be given, and the non-return pointer mechanism will probably jam the cosine meter's wheelwork. It is evident that the graduations on the non-return pointer scale must become very open towards the upper end, and the important point on the scale, i.e. that for unity power factor, will be missing. In the minimum power factor arrangement, since the cosine meter with the contact-making device will not register at zero power factor, the power factor scale will have similar characteristics, and will be incomplete at the zero power factor end. A difficulty may also arise in dealing with loads occasionally having leading power factors. A sine meter will reverse when the power factor leads, and a non-return pointer device may be very difficult to arrange on a meter which reverses, if one still expects to get the pointer to give an indication. I consider also that the suggested marking of the non-return pointer scale in kVA-hours (as an alternative to cos ϕ) would be very misleading. The term kVA-hours should plainly be reserved exclusively for the time integral of kVA. Here, however, the meaning of the indication on the scale can only be that so many kVA-hours have passed during the time that, say, 10 energy units have passed; and such an indication, while suggesting a true integration or registration of kVA-hours, really indicates nothing of the sort. At the present time there is a prevalent misapprehension as to the information given by a sine meter's registrations; there is, as a matter of fact, a grave fallacy underlying the employment of a sine meter. In this paper and in other publications it is implied or stated without any qualification that a sine meter used in conjunction with a cosine meter enables the true kVA-hours passed during a given period of time to be calculated. Now this is demonstrably untrue (except in the one exceptional and particular case where the power factor has remained absolutely invariable during the whole time under consideration, in which case, it may be remarked, a sine meter would hardly be necessary at all), and it is extraordinary that such an erroneous idea could be so persistent. Since so-called "average power factors" are calculated from sine and cosine meter combinations, and since in the aggregate large sums of money are paid by consumers on the basis of such calculations, it is well that it should be clearly known what a sine meter does, and does not do. Taking the author's symbols A and B to represent respectively the registrations in a given time of a cosine and a sine meter, it is erroneously assumed that the kVA-hours passed during that time are

$$\sqrt{(A^2 + B^2)}$$

Consider, however, three consecutive periods of time during which the power factor has assumed three successive different values, although it has remained constant during each one of the three periods. Suppose that the cosine meter's registrations for each of the three periods are A_1, A_2 and A_3, and that the sine meter's registrations are B_1, B_2 and B_3. We can then accurately state that the true kVA-hours for each period are respectively $\sqrt{(A_1^2 + B_1^2)}$, $\sqrt{(A_2^2 + B_2^2)}$, $\sqrt{(A_3^2 + B_3^2)}$ and that the true total kVA-hours for the whole period are

$$\sqrt{(A_1^2 + B_1^2)} + \sqrt{(A_2^2 + B_2^2)} + \sqrt{(A_3^2 + B_3^2)} \quad . \quad (1)$$

Now according to the fallacious assumption referred to above, taking the total registration on the cosine meter to be $(A_1 + A_2 + A_3)$ and on the sine meter to be $(B_1 + B_2 + B_3)$, the total kVA-hours would be calculated as

$$\sqrt{\left\{(A_1 + A_2 + A_3)^2 + (B_1 + B_2 + B_3)^2\right\}} \quad . \quad (2)$$

It is quite plain, however, that expressions (1) and (2) are not, in general, equal; and it can be proved that (2) is always less than (1) (except in the particular case when $A_1/B_1 = A_2/B_2 = A_3/B_3$). A few arithmetical examples would make the matter quite obvious. In other words, the calculations from a sine and cosine meter combination used over a period during which the power factor has varied, always give a quantity which is less than the true kVA-hours. The defect from the true value is the greater the more the power factor has varied, and may be very considerable, e.g.

as much as 30 per cent in some extreme cases. It would seem that this fact is of great importance and should be properly recognized so that engineers may not be misled by the suggested use of the formula $\sqrt{(A^2 + B^2)}$, and may not use the sine meter without fully appreciating the limitations of its usefulness.

Mr. H. D. Wilkinson (*communicated*): The paper contains a comprehensive survey of power-factor-correcting machines and appliances, and gives a useful review and criticism of existing tariff rates. But perhaps the best part is in the investigation into the most economic plant which should be used for power factor improvement, in other words, as to what expenditure in corrective devices is justified on a self-contained power plant so that the total capital cost is a minimum. The author shows that the power factor at which it is financially economical to operate the system is a function of the ratio of cost per kVA and per kW of the correcting and generating plants respectively, by the formula $\cos \phi = \sqrt{(1 - a^2)}$. This puts into mathematical form the truism that the more costly the corrective device the less the power factor of the system can be economically improved. In other words, the greater the amount paid for power factor improvement per kVA injected, the less the power factor can be improved with a maximum saving in total cost. This shows, therefore, what an important part would be played in the raising of power factors on distribution systems by the cheapening of corrective devices, and how much more could be done economically with low-priced phase advancers. On the question of tariff it is undoubtedly correct, as pointed out in the paper, to give a financial inducement to the consumer to maintain a high power factor, but I am not convinced that the power factor on the consumer's peak load should alone be considered in the framing of tariffs. If his peak load coincides with the peak load on the supply undertaking's generators and transmission lines, that is no doubt the period most difficult to cope with, but it is almost certain that the consumer's power factor is higher during the peak-load period than at other working hours, and it would appear to be more equitable to the consumer and more advantageous to the supply undertaking to base the tariff on the average power factor. This could easily be observed by taking the percentage ratio of the readings of two single-phase cosine meters connected in two phases, while the arithmetical sum of the pair gives the total units consumed. The author has done well to point out the economically unsound tariff of price per unit based solely on power factor. In conclusion, I should be glad if Prof. Miles Walker in his reply would give us a little further information on the low-frequency a.c. excitation of synchronous induction motors, which he gave the impression of being so much more efficient than d.c. excitation.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

North-Eastern Centre, at Newcastle, 13 November, 1922.

Mr. J. M. Heslop: It is almost a platitude to say that the power factor problem has become of supreme importance to the electricity supply industry, for it is a characteristic of alternating-current distribution, whose field of influence is already wide and its significance rapidly increasing. The transformer and the induction motor—two appliances whose invention has facilitated the expansion of electricity supply and distribution to an extent which can probably scarcely be over-estimated—each possesses a characteristic, i.e. the need of magnetizing current, which in its present-day dimensions is becoming a source of embarrassment. The problem of supplying this magnetizing current has become of such importance that in a multiple-station undertaking it is sometimes worth while to relieve all but one of the stations from wattless power and transfer the whole of it to the remaining station. One American undertaking, for example, generates the whole of the wattless power of the system (30 000 kVA) by steam during the summer, in order that a distant hydro-electric station may operate at unity power factor and utilize to the full the ample flow of water then available. While certain portions of the transmission and distribution system contribute their quota to the total magnetizing current required, I think it may safely be considered that the widespread use of the induction motor is the principal source of the trouble. The author rightly lays emphasis on the view that the consumer cannot be absolved from complicity in the trouble, and on this point I would reiterate my remarks in the discussion on Mr. Carr's paper, namely, that the man who takes excessive wattless current to suit his own convenience should pay for the privilege of so doing. This paper contains an excellent summary of the possible methods of making him do this. The magnitude of the problem can be visualized when one considers that under present conditions of working in this country there is annually incurred, at a very modest estimate, an excess expenditure on coal alone of well over £500 000 beyond that which is necessary, and in addition to this there must be an unproductive capital expenditure of not less than 20 million pounds—expenditure which could have been applied to new connections or in other revenue-producing directions had it not been for the power factor bogey. The author says on page 92: "It is, therefore, to the supply company's interest that the consumer should have a good power factor not only at peak load, but also at lower loads." I should prefer to re-write this statement somewhat as follows: "It is the duty of the consumer to have a good power factor not only at peak load, but also at lower loads, for in the absence of a power factor clause in the tariff the man with a good power factor on his installation is bearing part of the standing charges which ought to be met by his neighbour." The remedy for the evil of bad power factor is two-fold; the first stage is preventive and consists of missionary work amongst consumers; the second stage is punitive and involves the imposition of stiff penalties for bad power factor, with a corresponding bonus for improvement. The corrective

methods which may be employed are numerous, as can be seen from the paper, and it is not feasible to say dogmatically that any one is the best. Each has its proper sphere, but of the importance of the problem and the value of the paper there is no room for two opinions. The subject of power factor correction is receiving a great deal of attention at present, but not more than it ought to have nor more than it will have as time goes on, for it is one of the foremost problems facing electricity supply undertakings to-day. Power factor is, in fact, becoming for the electricity supply industry somewhat of a Frankenstein, and it has occurred to me that the whole power factor question is really a wonderful advertisement for the high-tension d.c. system.

Mr. T. Carter: The practical development of our art and of our industry has been bound up to an extraordinary extent with the work of Dr. Kapp. In 1885 and again in 1886 he read papers on dynamo design that threw a flood of light on much that was then dark, and now he has left behind him one that will certainly be of enormous assistance to us all in the consideration of a very tangled and difficult problem. It is, I think, particularly useful in the section on synchronous induction motors, because of the details of designs collected there, and because of the clear way in which it shows that this type of machine to have a respectable overload capacity must work at a leading power factor, or, if that is undesirable, an abnormally large machine, correspondingly expensive, must be chosen. Written by an independent expert, the paper is free from bias; all manufacturers and suppliers are apt to have their own fancies about what is best, but here we have a general impartial survey of the whole problem. Although a simple rule is given for the amount by which it is useful to improve power factor in a new and straightforward case, it is carefully pointed out that these simple cases seldom occur, and the most diverse considerations have to be taken into account in settling the best course to pursue. The counsel given is to apply power factor improvement with discretion and not to imagine that the more the power factor can be increased the better. The limits of the several possible devices are clearly shown. When correction has to be applied to an existing installation, no nice balancing of relative costs is usually possible, and only a rough approximation can be made to the most economical amount of improvement. The injected kVA are represented by ($\tan \phi_0 - \tan \phi$), and the improvement in power factor is represented by ($\cos \phi - \cos \phi_0$), and since $d \tan \phi / d \cos \phi$ is a minimum when $\cos \phi$ is $\sqrt{\frac{2}{3}}$ or 0·8165, correction is most cheaply obtained at that value. But the curve of relative rates of change of $\tan \phi$ and $\cos \phi$ is approximately horizontal between $\cos \phi = 0{\cdot}60$ and $\cos \phi = 0{\cdot}95$, both lagging, and practically exactly so between $\cos \phi = 0{\cdot}70$ and $\cos \phi = 0{\cdot}90$, and the correction required for a given amount of improvement is reasonably constant within this range of values. Outside this range, including, therefore, a change from lagging to leading power factor, the kVA required for a given correction become excessive. It is so difficult to get exact data that usually neither consumers and their advisers on the one hand, nor manufacturers and suppliers on the other, are in a position to furnish information to serve as the basis of a just bargain. All purely commercial bargaining is bad both when it is based on guesswork and when it is not; suppliers throughout the whole country should make up their minds to a principle, and adhere to it. One supplier comes to a consumer and says that the power factor of his motors must not be less than 0·90. When he is asked whether he means at full-rated load, or at full ordinary duty, or under any conditions of load whatever, he begins to feel doubtful. Another says that new apparatus should work at unity power factor, and that it would be even better if a slight leading power factor were used. That is true, but better for whom? And how is the ordinary consumer, even the large and well-advised consumer, to know when the terms offered are fair both to him and to the supplier? I know of cases where important consumers have complained that the price adjustment for variations in the price of coal is unjust to them, and they have supported their plea by quoting figures. They may be quite wrong, but an independent investigation of the effect of all sorts of varying factors on the cost of production would restore confidence, and would react to the benefit of the suppliers. There is an infinite variety of applications of electrical driving. Some of them require a large number of small motors, while others can use a few large motors, and there is much to be said for the principle that a consumer should not be penalized because he is a small-motor man, whose installation will tend to work at a lower power factor than that of the large-motor man. The vital question is whether each is doing his electrical driving in the best possible way. If any consumer so arranges his drives that his power factor is needlessly low for his type of installation, he ought certainly to pay for that bad design; but so long as he does the best possible for his own job, the suppliers ought to be satisfied without requiring him to pay more per unit because of things over which he has no control. After all, power factor difficulties arise because suppliers use alternating current for their own convenience, and not for their consumers'. The paper suggests that it is detrimental both to the supplier and to the consumer if the power factor is low: I suggest rather that the bulk of the burden is on the supplier, but it is not of his own choosing, and he ought not to grumble at the characteristics of consuming apparatus that must be used merely because he offers an alternating-current and not a direct-current supply. I think that suppliers should not expect to be recompensed by each consumer in exact proportion to the badness of his power factor for their greater expenditure on plant; they have a monopoly of the right to supply, and they are, therefore, public servants, bound to consider each consumer from his point of view as well as from their own. By being essentially fair to each member of the community they will be fair to the whole. That is one reason why the maximum-demand system of charging is, as the author points out, so much better than the others; and even that system should be carefully applied when the fixed payment is not purely on a kWh basis, but on a kVA-hour basis or on one intermediate between the two. I should be inclined to fix, as the ideal, not unity power factor in every case, but some

figure suitable to the type of installation, perhaps as high as 0·95 in the best cases and as low as 0·75 in the very worst, depending on the average size of motor that ought to be employed for the work and its usual best commercial power factor. I would then determine the maximum demand figure from the maximum kW demand by multiplying it not by 1/(energy factor) but by (ideal power factor)/(energy factor), so that if a consumer using small motors were enterprising enough to put in a type with unity power factor he would benefit comparatively more, as he justly should, than the customer who has larger motors, since their power factor is already nearer to unity. For example, taking the symbols at the end of the paper, assume two consumers, A and B, each with a maximum kW demand of 1 000, but let A have an ideal power factor of 0·90, while B's figure is only 0·80. Then $P_0 = 1\,000$; and let m = £5 per annum, U = 2 000 000, and d = 0·48d. Suppose each consumer's average power factor is only 80 per cent of his ideal power factor, namely, 0·72 and 0·64, respectively, then A will pay £11 000 per annum and B £11 800, a difference of about 7 per cent, under the ordinary maximum-demand system; whereas if each of them improved his power factor to unity he would pay £9 000, although it is much more difficult for B than for A to reach unity power factor. But if the ideal power factor were used for the purpose of discrimination, and both consumers were still to work at 80 per cent of the ideal figure, each would pay the same amount, namely, £10 250 on the basis of the assumed rates, and if each of them then improved his power factor to unity, A would pay £8 500, while B would pay only £8 000, which would recompense B for his greater enterprise. It should be understood that the figures used are merely assumed, and probably the rates under the discriminative system would need to be higher than under the present maximum-demand system so as to maintain the requisite total revenue ; but the comparison between A and B at each stage is correct in kind, and I suggest that some such scheme as I have proposed would permit the conclusion of agreements between suppliers and consumers on a correct, logical, and mutually equitable basis. The essential problem is : A certain total sum must be received from the whole body of consumers in order that the supplier may have an adequate revenue : how is the demand for that total sum to be apportioned amongst the consumers so that each may pay his fair share ? It is this question of the determination of the just incidence of the charge on individuals that I think might be solved by the adoption of what I have called a discriminative system, which is a simple modification of the ordinary maximum-demand system. The author uses the term "energy factor" in a particular sense, and I think that the latter part of the paper would be more clearly followed if special attention were drawn to it where it is first used in the paper, perhaps by a footnote defining it more specifically. It would, in fact, be an advantage if it could have a special symbol instead of the common cos ϕ. One of the few slight weaknesses in the paper is in its symbols : P is used with different meanings in different places, and so is ϕ_0. The terms "cosine meter" and "sine meter" are also used in a particular sense in the paper, and without definition their meaning may not at first be obvious ; here again I should like to suggest that Professor Miles Walker might, with advantage, add some explanation.

Mr. A. B. MacLean : The author states on page 93 that "we may consider the installation of rotary condensers by consumers to be financially unsound." I am inclined to think that this statement requires some modification, as it appears to me that with the tariffs now offered by some supply companies, in which the power factor of the consumer's installation is taken into account, the installation of a rotary condenser should effect a considerable reduction in the total charges for current. If we take the example worked out by the author, apply one of the tariffs mentioned by him as a pre-war tariff, and alter this to present-day conditions, I think it can be shown that the installation of the 600-kVA condenser will show a good profit. In the example the maximum demand has been taken as 1 000 kW at a power factor of 0·75. The total kVA demand is, therefore, 1 333. After the condenser is installed the peak load would be 1 036 kW and the total kVA 1 075. The power factor of the installation is, therefore, raised from 0·75 to 0·965. If we take the tariff given on page 106, viz. £1 per quarter per kVA of maximum demand plus 0·25d. per unit, and bring this up to what would probably be a corresponding present-day tariff, we should have to allow an increase in the demand charge to cover extensions to the company's system at prices much greater than pre-war figures, and the unit charge of 0·25d., which is largely governed by the cost of coal, would probably have to be increased by more than 100 per cent. I suggest that the corresponding present-day tariff would be approximately 25s. per quarter per kVA of maximum demand plus a flat rate of 0·55d. per unit. Taking the author's figures of consumption, the cost of current to the consumer before and after the rotary condenser is installed would be as follows :—

Before installation of condenser.

1 333 kVA, at £5	£6 665
2 300 000 units at 0·55d. ..	5 270
	£11 935

After installation of condenser.

1 075 kVA, at £5	£5 375
2 383 000 units at 0·55d. ..	5 460
	£10 835

We therefore conclude that the consumer by installing the rotary condenser reduces his total bill for current by £1 100. This is a reduction of 9·2 per cent in the total cost of current. The author takes a figure of £3 per kVA as the cost of the rotary condenser, but I believe that at present-day prices this should be considerably less, and that the cost of the 600-kVA condenser should not be more than £1 200. A machine of this kind should need very little attention, and the average consumer installing it would probably not require to employ any aditional labour, but could make arrangements to have the machine looked after by the existing staff. The cost of attendance on this machine would

probably not exceed 10s. per week. The total costs involved in the use of the rotary condenser would therefore be covered by the following :—

Labour at 10s. per week	£26
Interest, depreciation and maintenance at 15 per cent.. ..	£180
	£206

If we subtract this figure from the total saving in the cost of current, we arrive at a net profit to the consumer of £894. Referring to the different types of synchronous induction motors described, I presume that the rotor of the machine indicated in Fig. 4*d* has a two-phase winding, that the two phases are exactly similar, and that each covers one-half of the pole-pitch. If this assumption is correct, then each phase carries the same current, and the distribution of magnetic flux produced by the rotor current alone would have a wave-shape with a sharp peak. If the voltage of supply to the motor varies approximately as a simple sine function, an additional flux of third-harmonic frequency would have to be produced by a current in the stator, i.e. the motor draws a magnetizing current from the line of third-harmonic frequency. This, of course, may be of very small magnitude, but I should be pleased to have Professor Miles Walker's comments regarding the possibility of such a current being produced by this machine.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

NORTH MIDLAND CENTRE, AT LEEDS, 21 NOVEMBER, 1922.

Mr. H. E. Yerbury : The technical and mathematical part of the paper admirably covers the field, and I shall, therefore, confine my remarks to the commercial aspect. As supply engineers, we know that a low power factor is a condition which confronts us—and not a theory. I submit that it is unreasonable to suggest that any consumer should take steps to improve his power factor unless a substantial rebate is given by the supplier. Every individual installation should be studied before a decision is made as to whether it is desirable and economical to install a device which alters the characteristics of the motors, or to deal with the problem of low power factor with static condensers on the cables supplying such motors. If the characteristics of the motor are altered, then the total costs involved must be taken into consideration. For instance, in many works no d.c. supply is available, hence the cost of a d.c. generator and the d.c. energy should be added to the cost of the phase advancer. This is not an expensive matter but apparently it is not taken into account in the paper. It is quite obvious that the improvement of power factor is tied up with the question of tariffs. A two-part tariff is, I think, the fairest all-round system of charging. In Sheffield we charge large power consumers £4 per kVA of maximum demand plus 0·25d. per unit, plus a sliding scale based on coal at 10s. a ton. Incidentally, a coal clause disregarding calorific value can be deemed neither scientific nor equitable. I think we can pass over the Arno system of charging, as it is hardly applicable to British practice. I think that the system adopted by the Clyde Valley Electric Power Company is the best submitted, although to my mind it is a debatable point as to whether a consumer of 250 kW should be charged a 20 per cent higher maximum-demand rate than a consumer of 1 000 kW. It is conceivable that the smaller installation could be running at a very high load factor compared with the larger installation, in which case the former may be of greater benefit to a supply department. A very great service has been done to the industry by the Electricity Commissioners in the 1922 Act. Under the Electric Lighting Act 1899 a consumer could elect to be charged on either a kVA or kW basis. Happily, that clause is now repealed and a supply authority can decide to charge any consumer either on a kW or on a kVA basis. For the sake of economy and efficiency I think that steps should be taken to enforce the system of charging on a kVA basis as soon as possible, ever remembering the word "expediency" and all that that implies, and that a satisfied consumer is the best advertisement for electricity. At the present time I find that it pays a consumer with a load factor of less than 30 per cent to be charged on a kWh basis, and only where his load factor exceeds about $33\frac{1}{3}$ per cent does it pay him to be charged on a kVA basis. Personally, I think that the best system for the supplier is to declare the minimum average power factor, say 0·8. Then the price per kVA of maximum or average demand above or below that declared power factor should be varied, and in addition a flat rate per kWh should be charged. To give a consumer the advantage of night-time phase-advancing might be advantageous to a power company with long transmission lines and only power loads, but that practice on a town's general supply cannot, I think, be generally recommended. It appears that three instruments are essential to ascertain a consumer's maximum or average demand, and also his kVA and kW consumption. There has been much discussion as to whether one should charge on a maximum demand or average demand over a predetermined period. I think that the average is fairer, and in most cases the average is taken over a period of approximately 20 minutes with a thermal instrument.

Dr. T. F. Wall : I have recently been engaged in studying a new device for the phase-advancing of induction motors, in which the electrical energy is stored during one part of the cycle in the form of chemical energy and during the remainder of the cycle is released in the form of electrical energy. The principle is thus the same as that of a secondary battery, such a battery being, in effect, an electrical condenser of very large capacity. Suppose two lead grids, say A and B, are pasted with red lead (Pb_3O_4), immersed in dilute sulphuric acid, and connected in circuit with an alternating-current supply. Then during one half-cycle

the paste of one grid, say A, becomes oxidized to the higher oxide and the paste on the other grid becomes reduced to the lower oxide. In other words, the arrangement corresponds to an accumulator on charge, the grid A being the positive plate. During the next

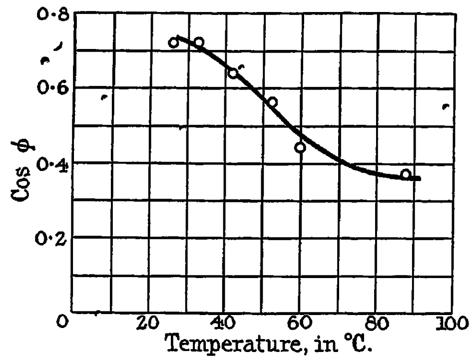


FIG. B.

half-cycle the action is reversed, and the cell becomes discharged and re-charged in the opposite direction. It is found that the action is greatly assisted and improved if the cell works at a relatively high temperature, say about 80° C. When the temperature is so

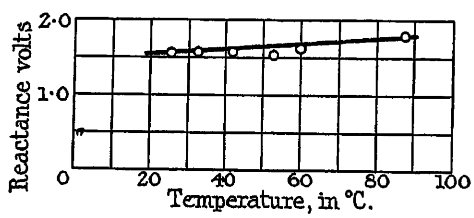


FIG. C.

increased the gassing becomes negligibly small and the inherent power factor becomes very low, that is to say, the losses are low and the phase advance of the current on the potential difference is large. In Fig. B this effect is clearly shown. The readings were taken by

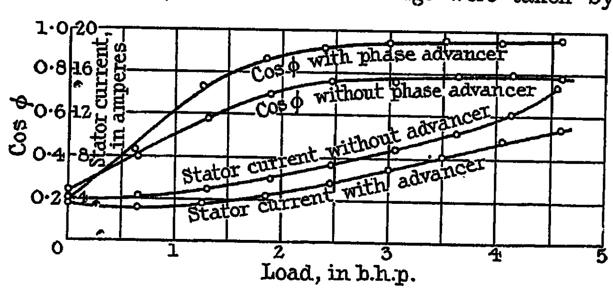


FIG. D.

connecting a cell to a low-frequency supply and immersing the cell in a bath the temperature of which could be regulated. It is clear that a very considerable improvement of the action of the cell takes place up to about 70° C. and subsequently the improvement is less marked with increase of temperature. In Fig. C the corresponding values of reactance voltage are plotted as a function of the temperature. The effect of increasing the temperature appears to be two-fold, viz. (i) The specific resistance of the electrolyte is reduced; and (ii) the chemical activity of the components of the cell is stimulated. With regard to the second effect, it is of interest to note that the action of a certain type of lightning arrester is based on the fact that the chemical stability of lead oxides is very easily upset by relatively small temperature-rises. Dry lead peroxide (PbO_2) has a specific resistance of about 1 ohm per inch cube, the resistance varying with the pressure with which the powder is compressed. At a temperature of about 150° C. lead peroxide is reduced to red lead (Pb_3O_4), which has a specific resistance of about 24×10^6 ohms per inch cube. At slightly higher temperatures red lead is reduced to litharge (PbO), which is practically an insulator.* In Fig. D the results of some tests on a 4 b.h.p. induction motor are given. These tests were made by two post-graduate students, Messrs. G. Allsop, M.Eng., and C. E. Robinson, M.Eng. The data were obtained with one cell in series per rotor phase, and clearly show the beneficial effects to be obtained by

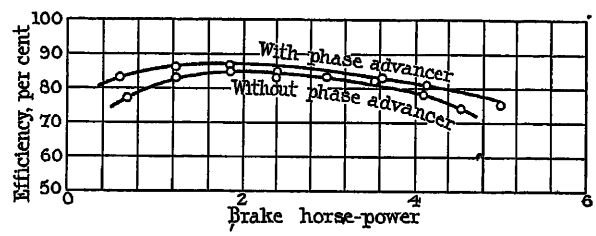


FIG. E.

this type of phase advancer. The tests also showed (see Fig. E) that the efficiency of the motor was greater when the phase advancer was in circuit than when the machine was running under the normal conditions of short-circuited rotor.

Mr. J. W. J. Townley: The paper is very interesting to all engineers concerned in the generation or distribution of alternating current, but what impresses one on reading it is the fact that so much has been done in the design and development of phase advancers and that so little use has been made of them in practice. The whole trend of the paper has been in the direction of encouraging the consumer to improve his power factor, but I think the improvement of the power factor of the system should be kept in the hands of the supply authority, who can put down phase-advancing plant in those areas where the mains are fully loaded, and when mains extensions are carried out can transfer the phase-advancing plant to another part of the system. It is usually the case that more copper has to be laid down than is required for the needs of the moment, owing to the heavy cost of reinstatement, and this copper might just as well be loaded by consumers who pay a standing charge based on their kVA demand. One has only to compare the tariffs of different supply authorities to note the very great difference between basing the standing charge upon kW and upon kVA, one undertaking quoting, say, £4 per kVA, and another £8 per

* *General Electric Review*, 1918, vol. 21, p. 597.

kW. If the consumer who is paying £4 per kVA has a power factor of 0·7 he is actually paying £5 14s. per kW. That difference represents a very substantial increase in the revenue of the supply undertaking, and this will be lost under present methods of charging, without much compensating advantage if the power factor improvement is left entirely in the hands of the consumer. I have had some experience with the Kapp oscillating phase advancers on two induction motor-generator sets, each of 1 500 kW capacity, ordered in 1914 and installed in 1916. These machines have operated in a perfectly satisfactory manner, and my experience has been such that I would always recommend the installation of induction motor-generators with phase advancers rather than synchronous machines, as the former give all the advantages of a synchronous set but with the great additional merit of simplicity of starting.

Mr. W. E. Burnand: The question is essentially divisible into two parts, one applying to the supply authority and the other to the user. So far as the supply undertaking is concerned it is a matter of simple arithmetic and a little judgment to correct the power factor when it is necessary and advantageous. As regards the consumer, the reason that this power factor question has become of importance is unsuitable tariffs. I should like to point out that the current taken by motors and inductive apparatus is quite easily divided into two parts, one at unity and the other at zero power factor, and it is easy to get meters to register these readily. The ordinary induction meter indicates the power units, and it is quite easy to get a meter that will show the consumption at 90° from those, i.e. the wattless kVA. Trouble results from this lagging current, which, while it may be wattless, is not, however, useless. The magnetizing current acts as a fulcrum for the power current to work upon. The wattless current costs something like $\frac{1}{4}$d. per kVA-hour delivered to the consumer. Why not install a meter and sell three units for 1d. and make a profit on it? I think the consumer would understand that. If these magnetizing units can be sold to him at a profit, I think it will be more satisfactory than having to make complicated calculations and using power-factor terms which would not convince the consumer that he was being charged on a fair basis. The paper describes really a very comprehensive collection of devices for improving the power factor, but they are all of them expensive, and I think most people would call them complicated. The number of parts is often more than in the original motor the power factor of which it is intended to correct. They also lower, as a rule, the efficiency of the plant. It is necessary to offer a strong inducement to a consumer before he will use such an arrangement. Excepting static condensers, these are chiefly adapted for large motors, which need not, however, have a low power factor, if run from $\frac{1}{4}$ load upwards, so that it ought to be exceptional to find a low power factor on a large motor. The paper gives me the impression that the power factor is very materially lower with these special machines with the exciter not working than in a standard machine. That is due to the larger air-gap and the higher density of the magnetic flux in the teeth of the special machine. It is impossible to make a small motor which will have as high a power factor as a large one, but it would appear possible to improve this without great expense or complication. It means making the auto-transformer part of the starter about four times normal size, and running the motor when on light loads on a lower-voltage notch on the starter. The cost would be small and, so far from introducing a complication, strengthens a weak spot. Even with the existing tariffs this will generally be profitable. The reason is that the auto-transformer if it is properly designed is a more efficient transformer than the motor itself. Therefore, with the motor at $\frac{1}{4}$ load the power factor will be over 0·7 and the efficiency will be practically equal to that with the motor running on full load. Losses in the motor are saved that will seldom pay less than 20 or 30 per cent on the original extra cost. Under present conditions people will not lay out more money than necessary, and these are not in such great demand as they used to be, but if there were a proper tariff, and if consumers had to pay for the magnetizing current, the power factor would be raised and the sales would increase.

Mr. W. A. A. Burgess: As a large user I should like to refer to a method of power factor improvement which has not been touched upon, i.e. the improvement of power factor by what is called in America "electrical service," that is, advice to the consumer as to the proper use of his electrical equipment. I had occasion to take over a works containing a large number of motors and found that the total power factor was 0·41. There was obviously something wrong and I found a number of motors running much hotter than their loads warranted. On some it was found to be a question of excessive air-gap. As there may be many users who do not know what air-gap means to them, and do not care, they should be kept informed by the power supply authority in whose interests it is to secure a good power factor. To give an instance of this, I found in the works in question that it had been the practice when a rotor fouled a stator to take out the rotor and take a cut off it in the lathe, to the detriment of the power factor and the insulation of the rotor laminations, whereas what really required attention was, in nearly every case, the motor bearings. The improvement of air-gap is often erroneously thought to be impossible, but I found it profitable to buy a new rotor in many cases where the motor was otherwise in good condition, while in other cases the only alternative was to replace the entire motor. If service advice had been given, neither contingency would have arisen and the supply authority would have had a better power factor. After improving the air-gap the various motors must be arranged to carry something like their normal load either by changing over or getting additional loads transferred to them. By a combination of these methods and a rigid specification for new machines the power factor of the works in question was raised to 0·7, no small achievement where 90 per cent of the load consists of induction motors. In connection with the general question of power factor I should like to ask Prof. Miles Walker if he can tell us the exact relation of the power factor to the starting torque as far as the economic design of a commercial motor is concerned. It has been found on occasion that certain motors of

the squirrel-cage type with a remarkably good power factor at half and full loads are apt to fail to start up against full load and in some cases less than full load. Is this a case of locking owing to a too small air-gap, or merely an accidental coincidence of low rotor resistance? I fail to see why there should be such a extreme difference between the costs of the various apparatus for correcting power factor. The figures, given by the author, of 10s. to £5 or £6 are surely a standing reproach against certain manufacturing sections of the industry. For less than 10s. per kW on a reasonably sized motor, say one of 500 h.p., one can get a Kapp vibrator complete with switchgear and the provision for excitation. I recently purchased one which is of the horizontal type with ball bearings. It was installed, connected and put into operation and has up to the present required no attention beyond general running maintenance. It improves the power factor most satisfactorily within the limits of the capacity of the motor to which it is connected, and has given no trouble whatever. It seems to me, however, that power factor improvers of the Scherbius and the Kapp vibrator type are only more or less able to supply power factor correction equivalent to the load on the motor, while a synchronous motor has its full capacity available for power factor correction at light loads as well as when doing useful work. One speaker raised the question of the cost of excitation. In the case in question the excitation was by a belt-driven 0·4 kW generator from the main shaft, and no trouble whatever was experienced. The cost of static condensers, which are a useful form of apparatus for the improvement of power factor, is alarming. That one should have to pay 3, 4 or 5 times as much for a static condenser as for a static transformer indicates to my mind a complete failure on the part of the manufacturers to cater for the industry at a reasonable price. It is a distinct advantage to be able to apply power factor correction to small motors, which probably form the bulk of a power-supply load and the aggregate power factor of which should be kept as high as possible. I think there will be very few power-supply authorities who do not desire all motors connected to their mains to have a power factor as near unity as possible. The question of improving power factor by static condensers has given me considerable food for thought, and as an alternative to a power-factor-improving device on the supply mains it has occurred to me that one might be able to use some form of condenser starter. The old water-resistance starter had an appreciable capacity, and if it were possible to go beyond that and use a variable-condenser device for starting instead of the customary auto-transformer starter, and then leave the condensers on the line while the motor is running and switch them off only when the motor is stopped, I think we should get something cheap, efficient and acceptable to supply authorities and consumers alike. I am quite aware that there are difficulties in the way, but I think they need not be insurmountable in these days. In regard to tariff, as a consumer and also as a supplier of electricity I agree with what has been said in connection with giving the consumer a fair deal. The consumer must be given all the satisfaction possible, and he must be shown that he is getting value for his money in every tariff offered to him, if the business is to grow and be profitable.

Mr. A. F. Carter: The manner in which some people—and in particular mechanical engineers—buy motors should receive attention. They have a machine they wish to drive and, as the manufacturers do not know what horse-power is required, they take a guess and add 50 per cent to it, and the result is perhaps a 10 h.p. motor for a 6 h.p. load. This is repeated, with the result that the mains are loaded up with useless kVA, whereas the energy actually used is very small. I think that much could be done by assisting the mechanical engineer in the selection of the powers required for his various loads. I recently had occasion to measure the load on a small motor of $2\frac{1}{2}$ h.p. The watt-hour meter was registering $\frac{1}{2}$ kWh per hour. This ridiculous—though not unusual—state of affairs should be remedied. On page 100, data relating to the Birmingham Corporation Electricity Supply Department are given, and it will be seen there that approximately one-quarter of the load is composed of rotary converters and one or two motor-generators with a corresponding high power factor balancing three-quarters of the load, which consists in the main of small motors at a low power factor, giving an average power factor of 0·79. No doubt if motors were better selected for their work the power factor could be brought up to at least 0·85 in the above case. I feel that one cause of difficulty is the fact that in some cases supply engineers rule that the current taken from the line must not exceed 125 per cent of full-load current. This often results in a larger motor being used than is necessary (particularly with squirrel-cage motors) in order to keep down the percentage overload current at starting. If the 125 per cent rule were suitably altered and more attention given to the selection of appropriate starting switchgear, no difficulty would be found in loading motors up to the 100 per cent mark.

Mr. A. V. Clayton: I think that the question of power factor is a burning one, especially, I presume, for supply companies, but I think that they are, to a large extent, to blame for that. Prior to the war I was engaged in designing machines on the Continent, and even small motors were being built with high power factors; for instance, machines of 6, 8 and 10 h.p. at 1 000 r.p.m., and of 10, 15 and 20 h.p. at 750 r.p.m. had power factors of 0·93 to 0·945 at full load, and of about 0·89 at half load. During part of the same period I was engaged in designing machines for some English manufacturers, and as the power factor permissible on the mains of the supply companies here was 0·8 we took advantage of this to design motors for the English market, regardless of power factor, so that they were the cheapest. Thus, whilst I was designing motors with power factors of upwards of 0·9 for use on the Continent, I was also designing machines with power factors of 0·8 and upwards for use in England. As regards the cost of rectifying low power factor by means of phase advancers, some little time prior to the war I built two 20-pole, 250-h.p. machines for use with Kapp vibrators as a trial of cost. They were bad

motors to design from the point of view of power factor, because they were comparatively small machines for the number of poles. As the number of poles in a machine increases, so the difficulties in obtaining good power factor increase, because the power factor depends to a large extent on the magnetizing current, and hence as the number of poles in a given size of motor is increased, the required magnetizing effect, and, therefore, the magnetizing current, is also increased. The two particular machines referred to were designed by me at Dr. Kapp's request to give the cheapest possible machine regardless of power factor, but with due attention to temperature-rise. Fulfilling these conditions the calculated natural power factor was 0·835 and on test 0·84. The cost of the Kapp vibrators was approximately 33 per cent of the cost of the motors, and even at that figure there was no profit to the makers on the manufacture of the vibrators. Had I utilized a little more material in designing the motors I could have improved their power factor to 0·92 at full load and to 0·87 or 0·88 at half load. The increase in cost of manufacture of the motors would then not exceed 12 per cent of their former cost, because the mechanical parts of the motors would remain the same, the labour would be practically the same and it would only be a question of using a little more active electrical material to obtain the higher power factor. The question of the length of air-gap, which of course has a very large bearing on the power factor of motors, is entirely a mechanical one and should receive due consideration with regard to the diameter and axial length of the rotating part and the rigidity of the mechanical parts of the motor. One speaker rather gave me the impression that the air-gap could be adjusted after the motor is built; this, however, is not possible except by building a new rotor, rather a costly proceeding. I was surprised to notice in the paper a statement that private enterprises had no interest in increasing the power factor of their load, and that the author had no personal experience where such cases occurred. I have known many cases of private generating stations desiring to obtain better power factors, and I can mention two cases in this country where I think it will be admitted that the improvement in the power factor of their own load was a distinct advantage. One was the case of a large cotton mill where a 1 000 kW generator was installed. This generator was an old type, low-speed machine and had a rather small magnetizing effect so that in time, as the load increased, it would not hold its voltage and the steam engine could not be utilized to anything approaching its full load. There were a large number of small motors, loom motors, etc., having bad power factors, and eventually a stage was reached where either further generating plant would have to be installed or else the bad power factor of the load would require rectification. This was done by installing a synchronous phase advancer at only a fraction of the cost of new generating plant. The cost of this synchronous phase advancer, or "rotary condenser" as it is sometimes called, was not nearly the cost (£3 per kVA) mentioned by the author. The cost was, in fact, considerably less than half this and at the time it was installed in 1917 was less than £1 per kVA injected, including the cost of exciter, etc. I think that the author also states that the cost of a synchronous phase advancer is the same as that of a generator of like capacity in kVA. This is scarcely the case, because in the phase advancer the mechanical parts are negligible and we only have to deal with the electrical energy; moreover, the speed can be chosen to suit the most economical design, whereas in a generator the speed is determined by that of the prime mover. (In this connection the fact must not be lost sight of that the highest-speed machine is not necessarily the cheapest.) Having regard to the electrical and mechanical conditions, each size of generator, or its analogy the synchronous phase advancer, has a definite speed for a given kVA output at which it can be designed most economically, and this speed nearly always differs widely from the natural speed of a prime mover of similar capacity. Many speakers have mentioned the number of small motors used on a supply company's network and it would be very interesting to know the average size of motor connected, because on that depends whether phase advancers could be used extensively to obtain a commercial advantage. In this connection I might mention that during my last year abroad the turnover of our works was a little over 110 000 h.p. of electrical machinery, and although machines of 500, 700 and 1 000 to 2 000 h.p. were frequent and nothing smaller than 3 h.p. was made, it surprised me to find that the average size of machine produced there was only about 32 to 35 h.p. Phase advancers of the Kapp vibrator type can only be used at a reasonably commercial cost in the case of fairly large motors, and it must be remembered that, apart from the vibrator itself, machinery to generate a supply of direct current must be provided with them (for excitation purposes) unless such supply already exists. Moreover, apart from the cost there is the question of a fairly complicated system involving at least three commutators per motor to be attended to, as against the simplicity of the straightforward induction motor which has done so much to popularize the use of electric power. My experience is that the Kapp vibrator cannot be used to increase the power factor beyond 0·96 to 0·98 (lagging) without disastrous consequences to the commutators, involving much wear and tear and very considerable attention. Rotary converters, also, work much better with a slightly lagging power factor, and attempts to over-excite them usually result in bad "hunting" effects. Kapp vibrators can be used to only a very limited extent, and for the production of an equal effect are probably the most costly piece of apparatus used for phase-advancing. Even on moderately large motors, where their use would improve the power factor from 0·92 or 0·94 up to 0·96 or 0·98, the extra complications involved outweigh the little advantage gained. It must be admitted that the Kapp vibrator gives constant power factor to the motor from about one-third full load up to full load, but large motors are usually fairly well loaded and a power factor of 0·88 or 0·89 could reasonably be expected, even at half load, without the vibrator. I believe that if statistics were made of the various supply companies' networks it would be found that even in all the isolated cases where Kapp vibrators,

rotary converters or other phase-advancing apparatus could be employed, the actual improvement at the power station would be trivial, and not nearly so much as could be obtained by the improvement of the power factor of small motors. My conclusion is, therefore, that power factor improvement should be sought primarily by removing the source of the trouble, viz. the bad power factor of the small motors.

Lieut.-Col. H. W. Watts (*communicated*): One speaker mentioned that engineers were sometimes responsible for installing a.c. motors which were unsuitable for their work, and thus obtaining a poor power factor. After the war I was acting as consulting electrical engineer for some factories in India and had occasion to superintend the erection of a large number of a.c. motors, the lay-out of which was designed by someone in this country. When they were set to work I found that the power factor of the installation was something under 0·4. The motors varied in size from 1 h.p. to 50 h.p. and the majority were of 25 h.p. I found that the reason of the low power factor was, in nearly every case, due to the motors running on a load far less than that at which they were designed to work. The makers guaranteed these motors to have a power factor of over 0·9 on full load and about 0·8 on half load. By re-arranging the motors to run on their proper loads, the power factor was improved and brought up nearer to the requirements of the supply authority, which was laid down as 0·85. I think it an excellent idea for a supply authority to have a clause in its tariff to power users to give the consumer a bonus should his power factor be better than 0·85. The Calcutta Electric Supply Corporation allows such a concession.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

Liverpool Sub-Centre, at Liverpool, 27 November, 1922.

Mr. E. M. Hollingsworth: The almost universal application of alternating current during the past few years has brought with it the problem of power factor improvement, and to the practice in many cases of installing electric motors of considerably greater power than is necessary, a relic of the direct-current days, is due in no small measure the low power factor with which many supply undertakings are faced. In view of this it is all the more necessary to keep in touch with consumers, and point out the advisability of installing motors suitable for the loads, letting them understand that the alternating-current motor is capable of withstanding considerable overload without any risk of failure. Regarding the various appliances put forward in the paper for compensating for low power factor, it seems to me that in many cases the static condenser has the advantage both as regards capital outlay and operating cost. Of course, in the case of large installations with motors of 100 h.p. and upwards installed, the synchronous induction motor or rotary type of phase advancer should be considered. Some months ago the company with which I am associated installed a static condenser in the small power station of one of their works, and we are very satisfied with the results. Before installing the static condenser the power factor was in the neighbourhood of 0·5, and the question of installing another generator at a cost of £3 500 was under consideration. The static condenser was installed for £700 and has improved the power factor to 0·85, with the result that the two existing generators are capable of dealing with the load. That part of the paper which deals with meters and tariffs is of great interest, and shows how necessary it now is for many supply authorities to adopt a tariff that will encourage power users to maintain the power factor of their load as near unity as possible. With recollections of the difficulty, years ago, of trying to explain to the prospective consumer the intricacies of the maximum-demand system of charge, it is to be hoped that history will not be repeated in this direction and that some suitable tariff will be arrived at which will take into account the power factor, and at the same time be simple enough for the ordinary consumer to understand.

Mr. L. Breach: I always feel that this subject is treated from the wrong point of view, and that there should be no necessity to improve the power factor of the system, but rather to improve the design of the apparatus connected to the system. One looks forward to the time when motors and other plant will have embodied in their design the necessary correction gear, and the motor with a high power factor will be started up in the same way as at present; perhaps in the future supply authorities will be able to insist on such plant being installed. Slip-ring voltages of the figure mentioned on open circuit will require special switchgear to protect the operator, and all apparatus must require little attention, because if one tries to persuade a consumer to install correction plant, his argument is that he must not only spend more on his plant, but must also give it more attention when he has got it. "Power factor" is an expression which should be capable of a simpler definition, as many engineers have a very vague notion of what it really means and of the far-reaching consequences in neglecting it. The consumer, of course, knows less; he gets several estimates for a motor, and on looking carefully over the efficiencies and weighing up the question as to whether eventually a more expensive motor with higher efficiency will not benefit him most, finds it will and orders the same. He studies the power factors and dismisses them as not being his business, but the supply undertaking's. In one instance with which we had to deal—a consumer with about 150 kW of proposed load—we installed a 300 kVA transformer in our substation to supply him at 400 volts. An inspector shortly afterwards informed us that the transformers were carrying 277 kVA. On investigation the consumer was found to have an actual load of 132 kW at 0·475 power factor. The matter was taken up with the consumer, who suggested that if our transformers were not big enough that was our

concern and not his, as he was quite satisfied with his plant. However, he was finally persuaded to re-arrange his motors to get better loading, with the result that he had several surplus motors to help in the equipment of a new factory which he was building. At the present time our system power factor on the peak is 0·95, with a daily minimum of 0·79 and an average of 0·883. This is, of course, exceptionally good and is accounted for by the large number of rotary converters in our converting stations. These converters are run with slightly leading power factor, and on peak load about 22 000 kW of plant of this type is running. There is also about 23 000 kW of 6 000-volt induction motor-generator plant installed in the converting stations, with an average power factor of 0·90 at full load. Perhaps this high power factor was attained by the designers at a sacrifice of safety, as originally we experienced much trouble due to stators elongating and rotors fouling. This was overcome by grinding the rotors, with a corresponding loss in power factor due to the increased air-gap. The d.c. load will not, of course, increase in the future nearly as rapidly as the a.c. load, so that unless some encouragement is given to the consumer or plant greatly improved, we must expect to lose the advantage which we hold at the present time. Up to now we have had no special charges on account of power factor, but the matter is under consideration as we are fully alive to the fact that something must be done. We feel, however, that with the numerous clauses already attached to agreements, the simpler the new arrangement is, the more readily it can be understood. The kVA maximum-demand charge with units charged on the flat rate by a cosine meter (as the author calls it) requires so much less explanation than the "preference and penalty" method, which becomes very complicated. We have considered giving financial assistance to the larger consumers to get them to install phase-advancing plant. In addition, we are constantly trying to persuade smaller consumers not to put in a 20 h.p. motor if a 15 h.p. motor will do the work, and are as constantly met with the reply that they prefer to have something in reserve. Perhaps they are right, but if the designer will produce a good piece of plant with a good power factor we shall agree with them entirely. In the meantime we shall do our best to maintain a high power factor, and we shall look to the motor designer to improve it for us.

Mr. H. Higham: The question of power factor improvement is rapidly becoming recognized as one of great importance, and the present paper gives consumers of electrical energy a very useful collection of various kinds of apparatus suitable for the purpose of power factor correction. With regard to the application of the various kinds of apparatus referred to, if a suitable load can be provided for a synchronous motor this method could be applied. If large slip-ring motors are available, phase advancers can be applied if the conditions are favourable. In the case of squirrel-cage motors, static condensers only are applicable. Rotary condensers are sometimes applied to long lines where lagging or leading load is necessary in order to control the voltage and power factor at the end of the lines. In all cases full details of first cost, and particularly of running losses, must be carefully compared before a decision can be made as to which apparatus is most economical. It frequently occurs that the first cost of a static condenser is higher than that of other apparatus put forward for power factor correction, but on comparing the running losses and the amount of attention required, etc., it is found that the static condenser is cheaper in the long run. I have frequently seen cases where a synchronous motor has been put forward for power factor correction, and for doing useful work. In some of these cases the arrangement is not very economical. Take, for example, a system which requires 270 leading kVA to give 90 h.p of useful work. This requires a synchronous motor capable of giving 280 kVA. The losses would amount to 14 kW and at 7 000 hours per annum at 1d. per kWh would cost £410. If, on the other hand, a 90-h.p. motor had been installed to do the useful work, and a 270-kVA static condenser, the losses in the complete equipment would amount to, say, 5 kW, and at 7 000 hours per annum at 1d. per kWh would cost £146, showing a saving of £264 per annum. With regard to the prices mentioned in the paper, viz. 10s. per kVA of correction for a phase advancer when used with a very large induction motor, some figures of the cost when used with motors of, say, 50 or 100 h.p. would be useful, as the greater number of power users are interested in motors of such sizes. I am inclined to think that the cost would then be more in line with that of static condensers. A supply undertaking when determining the charges to be made have to take into consideration the power factor of their system, and if they do not discriminate with regard to the power factor of each consumer it means that consumers with a good power factor have to pay more than they should to make up for those with a bad power factor. Moreover, it is not right that a consumer with a bad power factor should interfere with the voltage of supply, as is the case when working at a low power factor Penalty clauses are nearly always included in agreements but in many cases are not enforced. I believe that if a suitable accurate kVA meter were available, it would be of considerable assistance in helping supply undertakings to arrange their tariffs.

Mr. F. J. Teago: I should like to call attention to the footnote on page 90. This can be used to illuminate many of the author's points. Its most important use is that it enables the matter on page 91 to be represented in a graphical form which will appeal to those to whom mathematical equations convey no mental picture of the details involved. Set out the triangle OEI so that the angle ϕ_0 has a cosine equal to 0·75 (see also the note by Prof. Walker on page 90 and the author's remarks on page 91). Let the length of the vector OE represent the cost of the electrical plant at unity power factor, i.e. £12 000. The length of the vector OI will then represent the cost, £16 000, at a lagging power factor of 0·75, and the length of any other vector between the point O and the line EI will represent the cost at a power factor equal to the cosine of the angle between that vector and the vector OE. Now, to a suitable scale, the length of the vector IE

represents the cost of the power-factor-improving plant. If the value of the ratio $c/C = 1 \cdot 0$ then the scale of EI equals the scale of OE. In this particular case c/C equals $0 \cdot 25$, so that the scale of EI is four times that of OE. Mark off from I, along IE, a cost scale as shown in Fig. F and join O to convenient

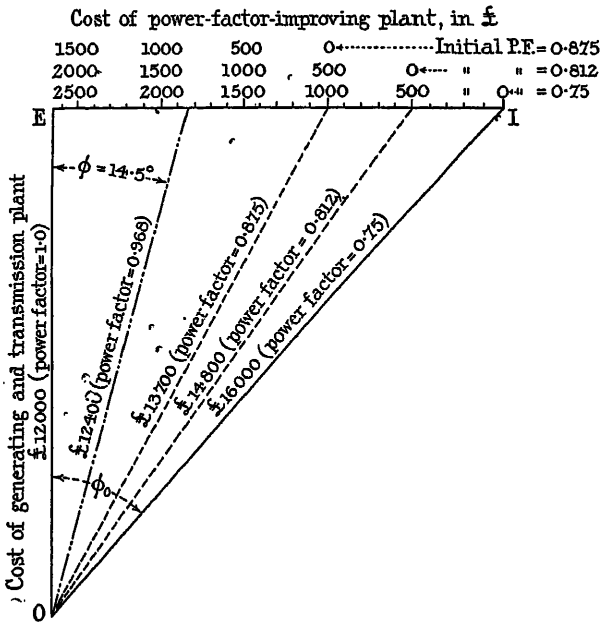


FIG. F.

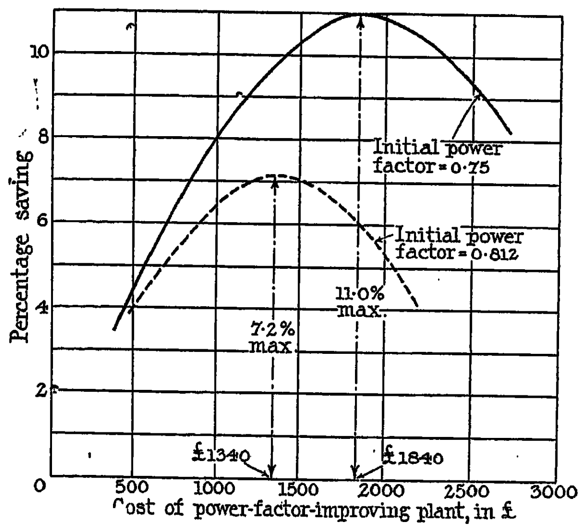


FIG. G.

points on this cost scale. Then, on improving the power factor from $0 \cdot 75$ to $0 \cdot 812$, the net saving will be

Original cost of plant — New cost of plant — Cost of power-factor-improving plant

$$\text{or } £16\,000 - £14\,800 - £500 = £700$$

The percentage saving $= 700 \times 100/16\,000 = 4 \cdot 4$ (approximately).

Repeat this for other values of the improved power factor and plot the results as shown by the full-line curve in Fig. G. This curve shows that the maximum percentage saving equals $11 \cdot 0$ and corresponds to an expenditure of £1 840 on the improving plant. From Fig. F it is seen that the angle at which this maximum occurs is $\phi = 14 \cdot 5°$ and that the power factor is $0 \cdot 968$. Now take an angle, to commence with, having a power factor of $0 \cdot 812$. The zero value of the cost of the improving plant under these conditions coincides with the original value, £500. On improving the power factor from $0 \cdot 812$ to $0 \cdot 875$ the net saving will be

$$£14\,800 - £13\,700 - £500 = £600$$

The percentage saving in this case $= 600 \times 100/14\,800 = 4 \cdot 1$ (approximately).

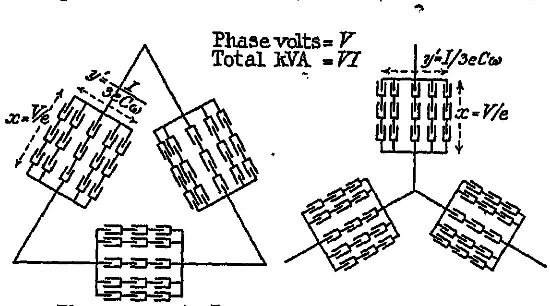
Repeat as before and plot the results as shown by the dotted curve in Fig. G. This shows that the maximum percentage saving is $7 \cdot 2$ and corresponds to an expenditure of £1 340 on improving plant, and it is seen that an expenditure of £1 340 under the new conditions corresponds to exactly the same improved power factor as an expenditure of £1 840 under the old conditions. This constant angle ϕ equals $14 \cdot 5°$, the sine of which is $0 \cdot 25$. Thus, as the author points out, ϕ depends solely on the value of the ratio c/C and is independent of the original value of the angle ϕ_0.

Mr. T. E. Houghton: I think I am correct in saying that the mathematical determination given in the paper of the most economical value of the power factor to which a system can be brought only applies to a new private installation, and therefore does not hold in the case of a consumer whose present power factor requires improving. Nevertheless it seems to me to be possible to deduce a mathematical relation in this case also. The author at the end of the paper recommends a maximum demand tariff based on kVA. Assuming this to be the case, I find that the economical phase angle for a consumer so charged can be determined from the expression $\sin \phi = Y/X$, where Y = annual charges plus running charges per kVA of phase-advancing plant, and X = charge per kVA per annum of maximum demand. Shorter periods can, of course, be used to suit individual cases. Taking the usual values of X and Y, I find that $\cos \phi$ approximates to unity. It is also possible to deduce a formula for the case in which it is desired to reduce the losses in a transmission or distribution system by improvement in the power factor. This is rather more complicated, but I find that the economic phase angle is given by the equation $\tan \phi = (50/K) \times Y/M$, where K = percentage losses at unity power factor, M = actual cost per kW per annum and Y has the meaning given above. In this case also $\cos \phi$ approximates to unity. I think it is significant that the author's expression and those given above all give values of the economic power factor very near to unity, whereas it has been generally accepted that the improvement in power factor should not be carried much beyond $0 \cdot 9$. Turning to methods used for power factor improvement, several speakers have drawn attention to the fact that it is not generally possible to use a synchronous induction motor for this purpose. Taking the case given in the paper of a

1 000-kW installation which required 600 kVA of phase-advancing plant, the most economical power factor at which to operate a synchronous induction motor is 0·707, since the sum of kW and kVA is then a maximum. In the given case, therefore, a machine of 600 kW capacity would have been required, which is, of course, excessive. In a case on which I have been engaged with Mr. Hollingsworth, we had to improve the power factor of a 200 kVA load from 0·5 to 0·9, in order to avoid the purchase of a new generating set. This entailed the injection into the system of 125 leading kVA, and to provide this capacity by means of synchronous motors would have necessitated the installation of a 125 kW motor working at 0·7 power factor, i.e. more than the existing load. In any case, in our business we rarely require a motor of more than 25 h.p., so that power factor improvement by this means is impossible. Vibratory phase advancers were also out of the question, since no d.c. supply was available. The only solution was a static condenser, and this has been most satisfactory. Regarding the question of tariffs, it seems to be generally accepted that the maximum-demand system based on kVA is the most suitable. The metering problem, however, appears to be somewhat complicated. As far as I can see, with the exception of the Aron Meter Company's maximum-current meter, no attempt is made to determine the true maximum kVA, i.e. the maximum kW divided by the average power factor is taken as the maximum kVA. This being so, I should like Prof. Miles Walker to say what is the objection to a polyphase cosine meter, fitted with a Merz maximum kW demand indicator working in conjunction with a single-phase cosine meter connected in the same phase as one of the elements of the polyphase meter. From the readings of the two meters the average power factor can easily be determined, and hence the maximum demand in kVA.

Dr. E. W. Marchant : The paper refers to nearly every method of power factor correction, including the use of static condensers. It may be interesting to record the effect of capacity on long, overhead transmission lines. A long, overhead transmission line has very considerable self-induction, but it also has considerable capacity, and in one case that has been calculated of a 200-mile transmission using three overhead conductors each of 0·36 in. diameter, spaced 6 ft. apart, it may be shown that the capacity effect is very considerably in excess of the reactive effect due to self-induction. At 60 periods such a line, if supplying a load of 200 amperes at the receiving end with 60 000 volts between phases at a power factor of 0·9, will require at the sending end a pressure of 70 000 volts, and a current of 175 amperes at a leading power factor of 0·966. This voltage is, of course, low for a 200-mile transmission line, and the constants would have to be varied for a higher pressure. It is well to bear in mind that a phase advancer is specially adaptable to large motors. Some months ago I made an inquiry for one to be used in connection with a 10 h.p. motor, and its cost was very nearly as large as that of the motor. For motors of 100 h.p. or more, no doubt the phase advancer is cheaper as compared with the motor. The rating of the phase advancer for a given amount of leading kVA is only about 5 per cent of the kVA that is to be injected, since the current is injected into the rotor of the motor by the phase advancer at the slip frequency instead of at the line frequency. Consequently, the current required to produce the necessary compensation for the magnetizing current in the stator will have to be supplied at a much lower voltage. If the slip is 5 per cent the voltage injected will be only 5 per cent of that required at the line frequency. For small motors, static condensers are the cheapest method of correcting the power factor. For larger machines the phase advancer may be less in capital cost, but there is another point which must be taken into account. If we take a motor with a phase advancer working with a full-load slip of 5 per cent, and assume, for example, that it is necessary to inject 200 kVA of leading current, only 10 kVA will have to be injected by the phase advancer, but the power taken by the phase advancer will be from 1 to 1·5 kW. If condensers were used instead, with a power factor of 0·0016, the power that would be required would amount to only 0·32 kW, or, roughly, one-third of the power that is used by the phase advancer. The actual power loss is small and, therefore, the cost of the extra energy used per annum would probably be compensated for by the smaller capital charge due to the phase advancer. It would be interesting if Prof. Miles Walker could give in his reply any information as to the limit of power of motor below which it is not economical to use phase advancers.

Mr. J. C. Prescott : The number of condenser units required to absorb a given amount of lagging



Phase current = I/3 Phase current = I/3

FIG. H.

kVA is found from the equation $n = P10^0/(\omega c e^2)$, where P = lagging kVA, c = capacity of each condenser unit, and e = working voltage of each condenser unit. Although this would, in general, give the exact number, certain other conditions must be fulfilled for a balanced polyphase load. In the first case, n must be divisible by the number of phases, and, further, the units for each phase must be capable of arrangement in an integral number of lines, each line containing an integral number of units. Thus in the three-phase case shown in Fig. H there must be $I/3ec\omega$ complete lines in parallel, each consisting of $\frac{V}{e}$ units.

Mr. C. Rettie : The paper apparently deals only

with land practice, but the problem is, in many respects, applicable to the electric propulsion of ships, although the conditions of one may be different from those of the other. The first battleship in America fitted with electric drive had squirrel-cage induction motors having two windings on the rotor with high and low resistance, respectively. The efficiency was so low, however, that in the other ships fitted up by the General Electric Co. of America the system was altered, the principle being the same, but a winding on the rotor was introduced with slip-rings to raise the power factor, the winding being cut out when the motors were up to speed. In the later electrically-propelled ships in the merchant marine built in this country and America, synchronous motors have taken the place of the induction motor, on account of the high power factor to be obtained. In a paper * read before the combined meeting of the American Institute of Electrical Engineers and Naval Architects last winter in New York an interesting discussion took place between the author and Mr. W. L. R. Emmet, consulting engineer of the General Electric Company, on this question of power factor. The remarks of Mr. Hollingsworth would apply to land practice but not to the electric propulsion of ships, as a big reserve of power is essential. In a recently published report of a voyage of the U.S.S. "Maryland" (one of the latest American battleships to be fitted with electric drive) it was mentioned that at times, to maintain an average speed of 18 knots for the 7 000 miles covered, rough weather being experienced all the way, 8 000 h.p. above the normal had to be used. The propellers rising out of the water and the sudden loads thrown on the motors show, I think, that the conditions are totally different from those experienced in land practice. Phase advancers have not, up to the present, been used in connection with the electric propulsion of ships, but they were proposed by Mr. W. E. Thau in the paper mentioned above to raise the power factor of induction motors. Synchronous motors, even with induction characteristics, are not suitable for the electric propulsion of ships, except in the case of cargo ships where the question of efficiency does not apply so much as economy. In battleships and large, fast passenger liners where efficiency and control are of the greatest importance, however, the induction motor is the best, provided some means, e.g. phase advancers, could be adopted to raise the power factor.

Mr. A. E. Malpas: The paper gives a valuable review of the various methods of improving power factor, and I gather from the various remarks that have been made that, at all events for a moderate-sized installation, the static condenser method is still the best. With this view I agree, although in the future it may be that some of the more modern types of rotary device will become more and more adopted. The average user, however, attaches more importance as a rule to reliability than to the last word in improved power factor. As a user, therefore, I would ask those who are inclined to criticize too severely those of us who put in motors of a rather higher capacity than is absolutely required in normal working, to look at the case occasionally from our point of view. In the case of a large works running a continuous process, wherein one stage of the operations depends on the continuity of the previous stage, it is not permissible to have any avoidable interruptions, and the blowing of the fuses of a motor is, in general, one of the avoidable interruptions. In the case of water pumps, etc., it is easy to arrange the motor with a reasonable margin for safety, but in others it is not so easy, e.g. in haulage gears, furnace drives, etc., where the load may be very variable and a large margin over the ordinary average load must be allowed to cover possible contingencies. In such a works, considerations of power factor take a very minor place, with the result that the average $\cos\phi$ may be as low as 0·5, or even less. It is possible for this state of affairs to continue for years until the time arrives when, on account of extensions to process plant, the question of extensions to the electrical generating plant also arises and then it becomes necessary to consider devices for the improvement of power factor. Cases have been known where the expenditure of a comparatively small amount on static condensers has avoided a far larger expenditure on generating plant, but it would obviously be impossible, from capital considerations, to scrap a large number of motors in an existing works merely to substitute others of some of the types mentioned.

Dr. T. F. Wall: Professor Miles Walker has shown on page 102 how to deduce the magnitude of the con-

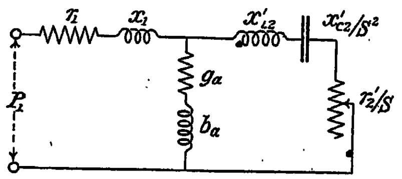


FIG. J.

denser capacity to which the vibrator is equivalent, and it is of some interest to obtain algebraical expressions by means of which the performance of the motor may be calculated for any value of the slip and of the equivalent condenser capacity. These expressions are most easily derived from the equivalent circuit by the use of complex quantities, and I give below the expressions so deduced for the stator current and for the torque. Similar expressions for the other characteristic quantities are easily obtained. The equivalent circuit for an induction motor having a balanced condenser system connected to the rotor slip-rings is given in Fig. J, where P_1 volts per phase is the supply pressure; r_1 ohms per phase is the stator resistance; x_1 ohms per phase is the stator reactance; x'_{L2} ohms per phase is the rotor inductive reactance reduced to the stator number of turns and stator frequency (i.e. the frequency when the rotor is stationary); x'_{C2} ohms per phase is the rotor condenser reactance reduced to the stator number of turns and stator frequency (i.e. the frequency when the rotor is stationary); r'_2 ohms per phase is the rotor resistance reduced to the stator number of turns; and s is the rotor slip. Further, assuming a three-phase stator winding, let u be the

* Journal of the American Institute of Electrical Engineers, 1921, vol. 40, pp. 1465 and 1519.

ratio of the number of turns per stator phase to the number of turns per rotor phase. Then for any value of the slip s

$$x'_{C2} = u^2 x_{C2} = \frac{u^2}{\omega C_2} \text{ ohms}$$

where C_2 farads is the actual value of the condenser capacity in the rotor circuit, and $\omega = 2\pi \times$ (supply frequency).

If r_2 ohms per phase is the actual value of the rotor resistance, then

$$r'_2 = u^2 r_2$$

If x_{L2} ohms per phase is the actual value of the rotor inductive reactance at standstill, that is, at the full frequency of supply, then

$$x'_{L2} = u^2 x_{L2}$$

For any value of the slip s the impedance vector of the reduced rotor circuit (Fig. J), is given by

$$Z'_{2s} = \frac{r'_2}{s} + j\left(x'_{L2} - \frac{x'_{C2}}{s^2}\right)$$

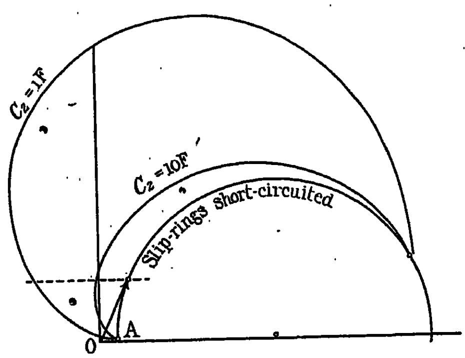


FIG. K.

The vector of the primary current may then be written

$$I_1 = P_1\left[\frac{1 + Y_a Z'_{2s}}{Z_1 + K Z'_{2s}}\right]$$

where $Z_1 = r_1 + jx_1$; $Y_a = g_a - jb_a$; $K = 1 + Y_a Z_1$.

Example.—A 50-h.p., 8-pole, three-phase induction motor with star-connected stator is connected to a supply pressure of 500 volts at a frequency of 50 periods. The constants of the machine are as follows:

$r_1 = 0\cdot129$ ohm; $x_1 = 0\cdot605$ ohm;
$Z_1 = 0\cdot129 + j\,0\cdot605$; $g_a = 0\cdot0038$ mho;
$b_a = 0\cdot0476$ mho; $Y_a = 0\cdot0038 - j\,0\cdot0476$
$r'_2 = 0\cdot165$ ohm; $x'_{L2} = 0\cdot545$ ohm; $u = 3$;
$K = 1 + Y_a Z_1 = 1\cdot029$ (very approximately);

$$Z'_{2s} = \frac{0\cdot165}{s} + j\left(0\cdot545 - \frac{0\cdot0286}{C_2 s^2}\right)$$

where C_2 farads is the magnitude of the capacity per phase connected in the rotor circuit. It is thus a simple matter to determine the locus of the primary current vector, I_1, for any value of the condenser capacity connected per phase in the rotor circuit. If the rotor slip-rings are short-circuited, this condition corresponds to an infinitely large value for C_2, so that $x'_{C2} = 0$, and

$$Z'_{2s} = \frac{0\cdot165}{s} + j(0\cdot545)$$

The formula for the stator current, I_1, then gives the ordinary circle diagram for the short-circuited rotor.*

In Fig. K are shown the current diagrams so obtained for the following three cases, viz.

(i) The rotor slip-rings short-circuited, i.e. C_2 indefinitely large.
(ii) A capacity of 10 F per phase connected to the rotor slip-rings, i.e. $C_2 = 10$.
(iii) A capacity of 1 F per phase connected to the rotor slip-rings, i.e. $C_2 = 1$.

It is interesting to note here that if the value of C_2 is made very small and eventually becomes zero, the current diagram shrinks to a point, viz. the open-circuit

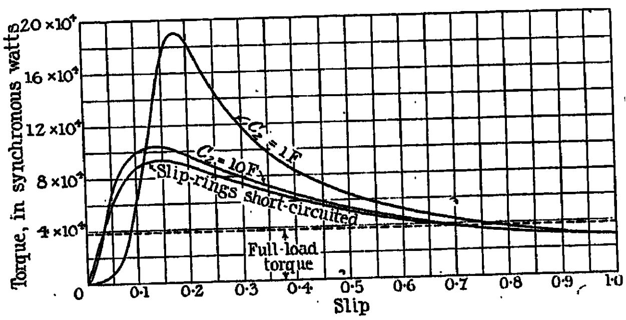


FIG. L.

point A. That this is so is apparent from the fact that when $C_2 = 0$ the condition is that of the open-circuited rotor. The torque of the motor is given by the following expression:

$$\frac{3P_1^2(r'_2/s)}{[(r_1+K(r'_2/s)]^2+[x_1+K\{x'_{L2}-(x'_{C2}/s^2)\}]^2} \text{ synchronous watts}\dagger$$

In Fig. L the values of the torque are plotted for the same three cases as are represented in Fig. K.

[Prof. Miles Walker's reply to the discussion will be found on page 134.]

* See E. ARNOLD: "Die Wechselstromtechnik," vol. 5, part 1, p. 68.

† The definition of the term "torque in synchronous watts" is as follows: the total power given to the rotor is the torque in synchronous watts and is equal to the actual torque on the rotor, multiplied by the angular velocity, in radians per second, of the rotating field. If it is desired to express the torque in pounds-feet units, then

Torque in lb.-ft. $= \frac{0\cdot737}{2\pi n_1} \times$ (torque in synchronous watts), where n_1 r.p.s. is the speed of the rotating field.

NORTH-WESTERN CENTRE, AT MANCHESTER, 28 NOVEMBER, 1922.

Mr. L. H. A. Carr: The information contained in the paper clearly falls into two classes. The first deals with the financial question, i.e. how the tariffs should be framed so as to allow for the division of the saving effected by the use of power factor apparatus; and the second concerns the actual apparatus which can be used for correcting the power factor. The first question—the saving to be effected and how tariffs should be made to meet the point—is one with which I cannot deal adequately; but I am glad that the author has stressed the point that, as the consumer has to pay for the power-factor-correcting apparatus, the supply authorities must persuade him to use it by making some difference in their tariffs. Some supply authorities do not give any rebate for a better power factor, and it is obviously not economical for the consumer to put in more expensive machines in order to get a better power factor, if he is to derive no benefit from doing so. The question of the improvement of power factor is, therefore, really in the hands of the supply authorities themselves; if they agree to make a tariff which will give some sort of a fair division of the saving, consumers will introduce the power-factor-correcting machine, but if no advantage is offered they will not do so. There is one type of machine for power factor correction which has been practically ignored in the paper. It is to be regretted that the author has said so little about the ordinary salient-pole synchronous motor with squirrel-cage starting winding. This machine is not described, as are other power-factor-correcting appliances, beyond the single mention on page 97 that one particular firm manufactures this type of machine. Possibly the author thought that it was too well-known to need description, but I suggest that it should be emphasized, particularly as the paper will probably become a classic, that the salient-pole synchronous motor with squirrel-cage damper windings for starting is probably the most widely used machine for power factor correction; and further, since names of manufacturers have largely been used in the paper, it should be recorded that this type of machine is made by, I believe, all the manufacturers of medium- and large-sized machines in the country. Since something like one-third of the paper deals with the synchronous induction motor, I propose to deal with this subject at some length. In Fig. 4*a* no exciter change-over switch is shown. It was the practice of the old British Westinghouse Company, and is the practice of the present Company, to use a switch, either single-pole or three-pole, to cut the exciter out of circuit when starting up. In fact, Fig. 4*g* shows the standard practice which has been adopted by this firm for many years. At the foot of page 97 the author states that it is modern practice to keep the moment of inertia of a synchronous induction motor as small as possible in order to render synchronization more easy. This point is really of no importance. Investigation shows that the modern synchronous induction motor will synchronize, at full load on 50 periods, against moments of inertia some 50 to 100 times the moment of inertia of the motor itself, with correspondingly greater figures for lower periodicities. The moment of inertia of the load is thus of far more importance than the moment of inertia of the motor. In one case recently where a synchronous induction motor was coupled to a large low-speed mine fan, it was found that at full load the motor would synchronize against a moment of inertia 9·7 times that of the combined fan and motor, while in the case of the high-speed compressors with relatively light flywheels the margin is very much greater. On page 95 the author states that the direct-current excitation on the "star" connection must be $\sqrt{2}$ times as big (in amperes) as the synchronous alternating current per phase for the same copper loss. Referred to the fundamental sine wave of the ampere-turn space curve, which is the useful portion of that curve, the M.M.F.'s due to these two currents are identical. This, however, is not a complete statement of the case, since, if the excitation were fixed at the above figure, the pull-out torque as a synchronous machine would equal the full-load torque, and so the actual direct current applied must be increased. If saturation be neglected, the excitation current will be exactly proportional to the pull-out torque. This means that, under the conditions stated, the exciting current in amperes must be from $2\frac{1}{2}$ to 3 times as great as the asynchronous secondary current at full load. Methods of reducing this ratio by different arrangements of the windings have been discussed elsewhere.* While it is true for the "star" connection that the same M.M.F. is produced for the same copper loss by direct current as by alternating current, it does not always follow that the same copper loss is always accompanied by the same M.M.F. Working again in terms of the fundamental sine wave of the ampere-turn space wave, it is found that with either of the distributions corresponding to the two limiting conditions of three-phase excitation, that is to say, the phase bands carrying currents in either the ratios 1, $\frac{1}{2}$, $\frac{1}{2}$, or 0·866, 0·866, 0, the losses for the same ampere-turn curve are the same. This includes three-phase windings and also the single-phase winding where the correctly spaced two-thirds of the rotor periphery carries the excitation current, the remainder being idle. If the rotor be given a uniform current distribution, however, as in the case of some of the windings illustrated, then, other things being equal, the copper loss for the same ampere-turn wave will be increased by 12 per cent. The "ingenious arrangement" illustrated in Fig. 4*f* is merely the well-known star-delta connection with one leg omitted. With reference to Fig. 8 and similar diagrams in the paper, it should be emphasized that the right-hand circle truly represents the asynchronous operation of the machine only when the exciter is cut out of circuit. It does not represent what really happens when the machine is overloaded and falls out of step as a synchronous machine, as under these circumstances, in addition to the induction motor current shown on the diagram, there is superposed on it a large

* See, for instance, L. H. A. CARR: "Induction-type Synchronous Motors," *Journal I.E.E.*, 1922, vol. 60, p. 165, and the discussion thereon.

oscillating current due to the synchronous action of the machine, which causes heavy surges in the line and which persists so long as the exciter remains in circuit.

Mr. S. J. Watson: The question of power factor correction is daily becoming of greater importance. Some few years ago when three-phase a.c. distribution commenced, it was not of much importance, because mains were not utilized to anything like their full capacity; but as the load increased and the power factor fell, difficulties have been experienced in obtaining the full advantages from the material provided, and anything that can be done to improve the power factor is in the right direction. Those who are engaged in industrial areas know quite well that the main cause of a low power factor on a supply system is the use of motors on a very small percentage of their full-rated duty. This occurrence cannot altogether be provided against, although I think that some improvement in that direction is taking place by grouping machines on a motor instead of utilizing individual drives. In any case the advisability of raising the power factor so as to approach unity is important by reason of the extension of the use of a.c. supplies. Towards the end of the paper the author deals rather fully with the matter of charges and this undoubtedly demands attention, because if money is spent on generating and transmitting a certain kW demand with an assumed power factor, if the power factor is lower than anticipated the capacity of the equipment is reduced, and it is impossible to obtain the income which would otherwise be available. All supply undertakings have not, as yet, adopted a tariff based upon kVA demand, but are still continuing with a charge per kW. Sooner or later some modifications will have to be made to compensate for the money spent which is not being fully utilized. My own view is that there should be one tariff based upon the actual kW demand, and then a somewhat lower figure for the difference between the kW and kVA demanded, because the costs which are incurred in connection with generating a supply, and its transmission, are not all based on kVA. For instance, the costs incurred in connection with boiler-house equipment, prime movers, condensers, etc., depend solely on the kW demand and are quite unaffected by the kVA demand. I do not think, therefore, that one is entitled to charge the same price per kW and per kVA. The fairest way would be to charge, say, £4 or £5 per kW demanded and make a lower charge, say of £3 or £4, for the difference between kW and kVA. Such an arrangement would ensure to the undertaking an adequate income from the money spent, which is the main object of a tariff. Regarding the provision of power-factor-correcting devices, it is perhaps unfortunate that individual pieces of apparatus cannot be made so that they are self-compensating, but in the majority of cases it will be found expedient for the consumers themselves to install the necessary apparatus, and they will be encouraged to adopt this course if the tariff is designed to secure to them an appreciable reduction in their accounts.

Mr. G. G. L. Preece: The paper shows how many different pieces of apparatus have been evolved for the purpose of power factor correction; but I should like to ask what is the use of spending time on such apparatus if we cannot persuade the municipal bodies or the power companies to push the matter. The question will certainly lag unless something is done. Municipal engineers have an association of their own. I suggest that some of their members should deal with the subject and formulate some fairly uniform system of charging, coupling with it a simple way of explaining the conditions of power factor correction. It is difficult to get Lancashire mill manufacturers to discuss this question, but if it could be made more thoroughly understood much more apparatus would be used, which of course would be ultimately for the benefit of the power stations. The power companies appear to have considered the subject of power factor correction more than the municipal authorities; probably because they have to look after everything in the way of getting as economical a supply as possible and obtaining the maximum revenue. Until something general is done I am afraid that power factor correction will remain where it is. I recognize that many of the larger municipal stations have seriously considered the question and have given benefits for high power factor, but there are a large number of smaller industrial towns which have done little or nothing. The paper is an important one and I am sure that it will lead to the building of a great deal of additional apparatus.

Mr. H. C. Lamb: On page 92 the author states that he is "not aware of any instance where a consumer drawing his supply from a thermic works has put up a rotary condenser on his own premises for power factor improvement." If the Manchester generating stations are "thermic works" then there is an instance where a rotary condenser has been installed on the consumer's premises for the improvement of power factor. That installation was made in 1917. I was much interested to see in the paper the figures given for the Birmingham Corporation power supply. Comparing the Manchester Corporation supply with that of Birmingham, and no doubt other undertakings, I think it is evident that the former is in a very happy position as regards power factor. That is because such a large proportion of the power is converted to direct current. With a load on the a.c. generators of about 80 000 kW one half is converted to direct current. The result is that at times of maximum demand the power factor in Manchester is over 90 per cent. Some of the converting plants have a slightly leading power factor and the remainder of the power supplied as alternating current evidently has a power factor of over 80 per cent, which seems a surprisingly good result. It is quite evident that so far as the Manchester public supply is concerned, the problem of power factor improvement is not so acute as it is with many undertakings, and that perhaps explains the difficulty which is in the mind of Mr. Preece. Probably most municipalities convert a considerable proportion of their power to direct current for traction supply as well as for lighting and power, and it certainly is not the fact that municipal engineers are less keen than company engineers on obtaining the most economical result. The real reason, I think, is that some power companies have no traction supply, and convert practically nothing to direct current, with the consequence that their power factors are often very low indeed. In

Manchester we have recognized the need for encouraging the consumer, and in our agreements with large power consumers there is a clause which gives a rebate and a penalty on high and low power factor, respectively. The author, I think, suggests that the fixed charge should be based on kVA and that that is the only sound system, but there is something to be said on the other side, because it is the continuous power factor and not merely the power factor at the time of maximum demand, that is of importance. It is also stated that some undertakings base their charges on kVA maximum demand instead of kW maximum demand, but I believe that very little has been done in that way. One reason for this is the lack of suitable kVA meters. In the Manchester tariff what has been aimed at has been to give the consumer a rebate on his converted power factor taken over a period, and we have taken a figure of 80 per cent as a standard. The average power factor is obtained by the readings of two single-phase watt-hour meters taken over a monthly or a quarterly period. If the average power factor so obtained is over 80 per cent the consumer is allowed a discount of 0·33 per cent for every 1 per cent improvement, and, similarly, there is a penalty if the power factor falls below 80 per cent. I should be glad if Prof. Walker would say whether, to take the simple example of a consumer with a demand of 1 000 kW and an annual bill of £10 000, if he improved his power factor from 0·8 to 0·95, for which, under the system I have mentioned, he would receive a discount of 5 per cent (that is, £500), that would make it worth his while to install power-factor-correcting apparatus and bear the losses in it.

Mr. L. Romero: I should like to associate myself with Mr. Preece's remarks. The information given in the paper as to the practice of various power companies in adjusting their charges to compensate for power factor is of great interest. The systems adopted all seem to be different, and in my opinion none of them is ideal. For instance, the system of charging so much per kVA instead of per kW is unfair, as it makes the low-power-factor consumer pay more than he equitably should, and the high-power-factor consumer less. It is, I think, quite time that the various supply authorities evolved a really equitable system of charging for power factor which could be adopted as a standard all over the country. It is important that any variation in price for variation in power factor should bear as close relation as possible to the actual difference in the cost of supplying. We, in Salford, have devised a system of charging for power factor based as nearly as possible on the actual costs. Our charge for energy is a combined one of so much per kW per annum plus so much per unit, and is subject to advances as the power factor falls below unity. These advances are graded to follow a formula which we have worked out. For example, the variation from unity to 0·9 is less than from 0·9 to 0·8, and so on.

Mr. G. S. Corlett: I propose to limit my remarks purely to one class of consumer in whom I am particularly interested, namely, mining plant. While one is, of course, familiar, so far as the general principle goes, with the various methods of improving power factor, in mining plant one has also to consider that all these rotating arrangements for the correction of power factor can only be applied when they are rotating. There are relatively few continuous operations in a colliery except the ventilation, and for many reasons one hesitates about installing synchronous motors for driving a mine fan. What I particularly want to emphasize is this. I am responsible for purchasing current under various types of agreements from public authorities and municipal authorities in different parts of the country, and the different principles of charging may be summarized as a plain flat rate, a differential rate—one rate by day and a lower rate by night and at week-ends—and the rest, by far the greater majority, on a maximum-demand kW-year basis, plus a unit charge. In many of those cases I have taken up the question of a consideration in the consumer's bill for an improvement in power factor, and in one or two instances have been met with a flat refusal. Obviously one cannot recommend a customer to spend any money under those conditions, because he will be in exactly the same position after doing so as he was before. In other cases I have had concessions offered, but the practical financial result has been so small as not to justify any expenditure. I am pleased to hear from Mr. Lamb that in Manchester there is a uniform bonus and penalty for variations up or down from a definite standard power factor. In a case which I had to consider quite recently the proposal was that the power factor was to be taken at 0·8; there was to be a very heavy penalty if it fell below this and an almost infinitesimal concession if it was exceeded. For that and other reasons the proposal was not accepted. I have used, with extremely satisfactory results, static condensers on colliery generating plants, and I believe that I installed the first such equipment on 3 000-volt mains. It has worked for many years without trouble or any maintenance costs. A condenser equipment possesses the following advantages, most, if not all, of which are absent in any rotary device: High efficiency; continuous operation; can be built in separate sections, which can be located at the points where the low power factor arises; and, consequently, line losses are reduced and line capacities increased.

Mr. A. B. Mallinson: On reading the paper I was impressed with the great advances that have been made since Mr. Carr read his paper last year.* I then ventured to suggest that the supply authorities should give an inducement to customers to install machines which would improve their power factor, and I was rather ridiculed for thinking that such a thing could be done. Another point that occurred to me as an adviser of consumers is this. One may be told: "Get the customer to pay for the improvement device when he is putting his machines in," but are these machines absolutely as reliable as the simple motor which otherwise would be installed? Particularly is this important when it is borne in mind that almost invariably there will be such a device on the most important drive in the installation, one that will run day and night. If a machine is to be installed that is more or less a box of tricks, and the risk of interruption of supply is thereby run, naturally the customer will hesitate. I was pleased to hear from Mr. Lamb that direct current still has some consideration in electric supply. I think that there is a lot to be said

* *Journal I.E.E.*, 1922, vol. 60, p. 165.

for direct current as against alternating current; and to hear that Manchester regards the direct-current load as being of great assistance from the point of view of power factor is very refreshing.

Mr. G. A. Cheetham : One speaker has commented on the diversity of charge in connection with power factor tariffs. In my opinion that is, to some extent, due to the difficulty of measuring kVA. If this did not exist there would be more uniformity in the methods of charging. In America a good deal of attention has been given to this subject of measuring kVA, and many wonderful devices have been produced to bring about the desired result. It is possible to get a fair approximation to kVA measurement, provided that the range of power factor change is known to begin with, and much work is being done in that connection at the present time. A customer wants to see a simple dial, to be able to read it in the way in which he read his watt-hour meter, and to compute the bill without using a slide rule. I think something will result from this extension of the range of power factor over which kVA can be measured, and in that event much of the diversity of charging will disappear.

Mr. V. Mallalieu : It has been remarked that the paper can be divided into two parts, first the financial and secondly the technical part. In spite of what has been said by the previous speakers the technical side has been quite well taken care of, and the author gives a number of different methods of improving the power factor. The static condenser method does not entail the use of running machinery; it has been applied to large plants and is absolutely reliable. I agree with Mr. Preece that if the supply authorities will begin to educate the consumer as to the advantages of power factor improvement, and give him a financial benefit, users in turn will buy the apparatus, which can be readily supplied. It is really a move on the part of the supply authorities which is wanted now. Mr. Watson remarked that the cause of bad power factor is largely to be found in underloaded motors and in the use of small motors. That is quite true, but I disagree with him when he advocates the use of larger motors and group driving as against the smaller motors. That is entirely against the trend of present-day practice and future development. The full advantage of electrical transmission is only obtained when the motor is brought up to the machine. In the case of a factory or a works it is no good bringing electricity to the factory and putting in a large motor in the place of a steam engine. The full advantage of electricity can only be obtained by subdividing the driving, and the choice of the size of the motors should be governed by factors such as works organization and the characteristics of the machines that have to be driven. We must give the best service possible for the particular operations involved, and leave the question of power factor improvement to the experts who are capable of dealing with it. I recently saw a curve, showing the changes during the last 10 years in the practice in American textile mills in regard to the size of motors. In this curve the average horse-power per motor was plotted against years, and it was astonishing to see how the average horse-power per motor had decreased in that period, the present average size of motor being only about 5 h.p.

Mr. E. P. Hill : In connection with the author's remarks on the rotary condenser, there are three 1 250-kVA sets installed on the South Metropolitan supply at Crayford, which are started up by starting motors on the self-synchronizing principle, the starting motor windings being connected in series with the main condenser windings. After the set has pulled into step these motors are short-circuited in the same manner as rotary converters. This considerably reduces the starting kick as compared with tap starting, and avoids the necessity of synchronizing, so that less skilled attention is required, the sets being ready for load in approximately 1 minute from standstill. The beneficial influence of a rotary-converter load upon the power factor of several municipal central stations has been brought out both in the paper and during the discussion, and the importance of this factor in actual practice warrants preferential treatment for the rotary converter over other types of converting plant, the power factor of which is not so good. Although the armature copper loss of a six-phase rotary converter will increase about 30 per cent for a 30 per cent wattless component, this copper loss is only a small part of the total losses in the converter. For example, in a 1 500-kW rotary converter the total loss would be of the order of 65 kW at full load and the armature copper loss at unity power factor, say, 12 kW, which would increase at 30 per cent wattless current to 15·5 kW and, together with the increased field loss, would bring up the total loss to, say, 70 kW, i.e. the total losses have been increased by 7·5 per cent only. The small extra copper required for this amount of wattless component can usually easily be accommodated and is advisable as a safeguard against overloads and improper use in service. A normal rotary converter is, therefore, capable of running with a reasonable amount of leading wattless component without any fear of serious overheating, so that approximately unity power factor can be obtained on the high-tension side of the transformer, the rotary converter taking care of its transformer magnetizing current and the necessary reactance embodied in its transformer for voltage control. If a heavier leading wattless current were required, it might become essential to reduce the d.c. output, but, as has been shown in the paper, most valuable improvement of station power factor is obtained by running at unity power factor or with only a reasonable amount of leading wattless current.

Mr. E. R. Fry : The importance of this subject from the supply company's point of view has scarcely been mentioned in this discussion. Loads have been steadily rising and in the case of some power companies it is not a matter of transmission feeders 12 miles long as mentioned by a previous speaker, but more nearly 100 miles. Lighting loads as represented by three-phase low-tension distribution networks have to be fed from the end of these long feeders, and the regulation of the line has to be kept very good indeed. Cases do arise when it is a question whether to lay duplicate lines or to install power-factor-correcting machinery, and I think that the tendency of the large power companies to-day is to adopt the latter alternative and improve the line regulation, rather than incur the expense of duplicate feeders.

Professor Miles Walker's Reply to the Discussion.

Professor Miles Walker (*in reply*): Several of the speakers, including Dr. S. P. Smith and Mr. Ayres, have spoken of the weak points of the synchronous induction motor. It is generally admitted that this type of motor when properly designed does the work required of it in a perfectly satisfactory manner and can be run at unity or a leading power factor. It is of interest to compare the performance of this type with that of an induction motor supplied with a Leblanc phase advancer. First, with regard to overload capacity, it is seen from the locus curve shown in Fig. 13 that the induction motor with a phase advancer can take a much greater overload than a motor having either of the locus curves shown in Fig. 5. One cannot, of course, count the Heyland circle as part of the locus curve of the synchronous induction motor, because the motor is not designed or intended to run on that part of the curve. The torque then is irregular and the power factor very bad. Even if the synchronous induction motor is over-excited so as to take full load at 0·9 power factor, the characteristic is not nearly so desirable in shape as that shown in Fig. 13. Now we have seen that to give the synchronous induction motor a reasonable overload capacity, it is necessary that it shall carry a very great field excitation, and this means more I^2R losses in the rotor than would be necessary in an asynchronous motor when taking normal load. That is one of the reasons why the synchronous induction motor costs more than the plain asynchronous type. In a great number of cases an induction motor fitted with a phase advancer could be built on a smaller frame than is ordinarily employed for a standard motor without phase advancer. This is because the phase advancer makes a little motor stand up to its work and one can safely put in a smaller motor to do the work, provided the average heating due to the load is not going to be too great. When phase advancers come to be made in greater numbers they should not cost much more than the exciters now supplied with the synchronous type. The average load on the phase advancer will be less. As against the slight disadvantage of having three brush arms to the d.c. exciter's two, the average current per brush arm will be considerably less than two-thirds of that required to be collected from the commutator of the d.c. exciter.

The Leblanc phase advancer may be regarded as an exciter in which the current slowly alternates and allows the motor to slip, while the power factor is kept near unity, or leading, as desired. There is practically no difficulty in the commutation, owing to the fact that the current is alternating slowly. In the problem of the commutation of a d.c. generator we must make provision for reversing the current under the brush in 1/1 000 second or less. It adds very little to the difficulty of the problem if the current is alternating at one period per second. The phase advancers which have so far been built commutate perfectly.

When advancers are standardized and manufactured in numbers the price should be very little more than the price of d.c. exciters, and can be partly, if not completely, paid out of the saving in cost of the main motor. The real reason why a very large number of phase advancers have not been sold in this country is that, until recently, very few of the supply companies had made it worth while for the consumer to improve his power factor. Now that concessions on a reasonable scale are being given, consumers are looking around for the best apparatus for the purpose. Where the a.c. motors are small the most convenient apparatus on the market is the static condenser.

Many of those taking part in the discussion have testified to the efficiency of the static condenser for this class of work. For big motors the Leblanc phase advancer contains less material for the same output than the Kapp vibrator, because it can be run at a higher average speed. Moreover, there is only one armature as compared with three armatures, and only one set of brushes per phase is required, instead of two sets. This reduces the brush losses.

As between the phase advancer of the Scherbius type having no field magnet, and one of the type described in the *Journal*, 1913, vol. 50, p. 329, having a field system designed to give an injected electromotive force of any required phase relation to the current, the latter type is much to be preferred in my opinion, for the following reasons.

By giving the injected E.M.F. a slight component in the same direction as the E.M.F. generated in the rotor winding, the slip can be reduced instead of increased, as described on page 101 of the paper. The effect of this is to reduce the size of the phase advancer. Now suppose that the slip of the motor were originally 1·5 per cent, then, taking the figures from page 101, a Scherbius phase advancer in order to inject 250 kVA on the primary side would need to have a capacity of 6·3 kVA if the slip were to be increased to 2·5 per cent. By using a properly designed field system the slip could be reduced to 0·75 per cent, so that the kVA rating of the advancer would fall to about 2·5 kVA. This would mean a much cheaper machine and would give better speed regulation on the induction motor. In the case of high-speed motors the advancers can conveniently be connected direct to the shaft.

When the induction motor has a squirrel-cage rotor it may in some cases be worth while to get the manufacturer of the motor to change the rotor to the slip-ring type having a winding suitable for the phase advancer.

There being very little iron loss in the rotor of an induction motor the temperature-rise is frequently very much smaller than that found in the stator. For this reason there is a tendency to reduce the amount of copper used in the rotor, the slip being increased accordingly.

If we consider the capital cost of the extra copper required to give a low slip, we find that the interest on this and the depreciation amount to very much less than the cost of the power wasted. Even if no advancer were used a rotor should (from the economic point of view) have about twice as much copper as is ordinarily used by the manufacturer, as long as prices

of power and copper are as we find them at present. If twice as much copper were to be put into the rotor winding it could carry the magnetizing current with the greatest ease and thus relieve the stator, which is usually very tight in design because provision must be made for high insulation, and for the iron and copper losses.

I do not agree with Mr. Ayres when he says : "It is not economical to correct power factor much beyond unity with phase advancers." The case for the induction motor fitted with phase advancer, and the synchronous induction motor fitted with exciter, are on exactly the same lines except that the heating for an average load is less in the case of the machine with phase advancer. It is mainly a question of whether we shall adopt a.c. or d.c. excitation. The a.c. excitation requires the smaller current at normal load.

As to the economical limit of size of machines to which phase advancers can be attached, my belief is that as soon as engineers awake to the true position, phase advancers will be made and standardized, and though at first they may not be supplied to motors less than about 100 h.p., it will be found that their cost will be so much less than that of static condensers doing the same work, that they will ultimately be used for smaller and still smaller motors until we have phase advancers of only a few watts' capacity.

The advantages of the static condenser for the over-excited induction motor, mentioned by Mr. Dorey, disappear as soon as a.c. excitation is employed.

In reply to Mr. H. D. Wilkinson, I beg to refer him to the following papers :

"The Improvement of Power Factor in Alternating Current Systems," *Journal I.E.E.*, 1908, vol. 42, p. 599.

"Design of Apparatus for the Improvement of Power Factor," *ibid.*, 1913, vol. 50, p. 329.

Many of those taking part in the discussion have spoken of the difficulty of explaining low power factor to their customers. If a charge were made on maximum kVA demand it would be sufficient to have an ammeter and to point out that the kVA is proportional to the reading. If the customer were allowed to watch this, he would soon understand how to operate his plant so as to keep down the maximum demand.

Mr. Edgcumbe's statement corroborates what is said in the paper and also by a number of speakers, viz. that a charge based upon maximum demand in kVA to pay for the capital expenditure, and another charge for kilowatt-hours supplied, constitute not only a simple but also probably as fair a method as any other.

I am glad that Mr. Teago puts the matter in a very simple light showing at once the relation between the various figures in the paper.

Mr. Houghton's comment in extending the theory to a case where an installation is already in being, is of great interest.

In reply to Professor Marchant, it is not possible to fix the limit of power of motors below which it is uneconomical to use a phase advancer. This is purely a question of standardization in manufacture.

The figures that Dr. Wall gives, relating to the condenser depending upon electro-chemical action, are of great interest, and it is hoped that this type of apparatus will soon be upon the market.

In reply to Mr. H. C. Lamb I would say in the first place that a rebate of only 0·33 per cent for each 1 per cent power factor improvement is very small. I presume that it is because Manchester is so well off as to power factor that it cannot afford a bigger rebate. Even with this small allowance it would be worth while for the consumer to install static condensers costing, say, £500 per 100 kVA installed. To improve the power factor from 0·8 to 0·95 in the case quoted would require static condensers having an input of 420 kVA costing, say, £2 100. Taking the interest and depreciation at 10 per cent, this would cost, say, £210 per annum. The losses in the condensers would be about 2 kW, costing, say, £20: total, £230 per annum to be deducted from the £500 rebate. The cost of improving the power factor would depend upon the kind of load and the apparatus available. A very favourable case would be where the whole load consists of new induction motors to be installed. In this case the motors could be built with extra copper in the rotors at an extra cost of £30, and phase advancers of 2 kVA capacity could be provided. Suppose these cost £70 ; the total capital expenditure would then be £100 (say £10 per annum). The total losses in the induction motors and phase advancers when running at 0·95 power factor would be less than in ordinary motors running at 0·8 power factor. The saving would then be £500, less £10, or £490 per annum.

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By Professor W. Cramp, D.Sc., Member.

(*Address delivered at* Birmingham, *25th October*, 1922.)

The story of man's work, individual or collective, is written not alone on parchment in ox gall and black ink, but on warmest human flesh in crimson blood. For every result of human endeavour, be it an Empire, Institution, Industry or smallest touching poem, some human being or beings must, in part at least, have died. This is a universal law, not sufficiently recognized in these days; that life, vigour, true vitality, can only be transfused—not created. For the realization of an idea a man will die, will give his life—give, I say, not sell. And this life, so given, will vitalize his idea, endow it also with the power of living in exact proportion as the life was given without grudge or reluctance. There is no surer way of discovering to what purpose a man lived than by the answer to the question: For what did he die? There is no better gauge of the stability and vitality of an institution than the exact tally of human beings prepared to lay down their lives *voluntarily* for its sake. Note how important is the qualifying adverb! Institutions may, in truth, be fed and maintained by wrongful human sacrifice, as much commercial enterprise has been, and doubtless again will be. But life acquired in this way is temporary, galvanic,—a mere Moloch life, and no true existence at all. To endow work, and the results of work, with true vitality we must give ourselves freely, without money and without price. This is the test of self-sacrifice, of real genuineness and sincerity.

I. Of a Man.

To the life and work of one who since the end of last session has left us, we need not fear to apply this test. But a few months ago he sat here in characteristic attitude with head bent forward, and keenest scrutinizing gaze; his piercing eyes half hid beneath the bushy overhanging brows. One look, one word, enough to tell us that here we have to do with a man, an individuality with purposefulness and intention flashing formidable from him. No mere commercial engineer this, we should say, with one eye upon his customer and the other on his pass book; but a forceful and resolute real-presence, not afraid of declaring that which in the round soul of him he feels to be true. A rugged and even despotic temperament, impatient of triflers, yet having withal that greatest of attributes, sincerity.

He had his hobbies too, this genius! All the more man for that, I think. Buying a house, adding a music room, living in it for a space, and again moving to repeat his experiment appears to have been one of them. No house was a home to him without a music room, it would seem. Since the invention of his vibrator, no public speech of his could avoid reference to that machine, it was said. Possibly so; but I will not believe that there was an ulterior and commercial motive in these references,—not if he could not live without a music room. Stratagems and spoils, I think, are not compatible with a music room.

He is gone from us. And so is Kelvin, and S. P. Thompson and John Hopkinson. They made a harmony in their time, this quartette! Kelvin in the highest soprano flights of physics, dipping ever and anon to indulge in the mezzo of engineering application. Thompson, the suave teacher and melodious alto of the group; half physicist, half engineer. Hopkinson, with his strong constructive sense, making great engines possible by his grasp of the principles upon which they depended, and Kapp, the engineer, to whom all pure physics was as nothing save in so far as it could be expressed in terms of veritable assemblies of finest materials made to serve the purposes of man. They have gone, I say, these four; but we still hear their harmonies and may yet read their scores, wherein they have recorded so much of their inner music as they could transmit to us their successors.

In the writings of Kapp we shall, if we search carefully, find the real entity lying behind his character, life and work, to which we may then apply our test of sacrifice. What was it that as a man, and a writer, he was concerned to do? Did he feel that he had actually and veritably some message from the True and Eternal as yet unwritten? Let us admit that there is no difficulty in selecting from a man's writings how much he did because the soul in him was longing to express itself, and how much for the publisher's fee. This I find not difficult, even in a case like that of Scott, where the true and the false are most closely intermingled. How much less in the case of Kapp, where true and false are almost synonymous with new and old! Truly, when a man chooses the written word as his medium, he declares thereby openly to what extent he is a preacher, what gospel or good news he has in him burning to deliver itself, and which must get itself declared, be it at the cost of his very life.

The good news which Kapp preached, as I read it from his writings, was in effect this: That electrical machines could be lifted from the region of the laboratory; could be designed on principles not very different from, and at least as certain as, those already current among mechanical engineers; that the formulæ of the physicist, enlightening as they were, could not be left for the engineer in the form of x, y, and z known or unknown: but that each symbol must to him stand for something of hardest fact, reducible to terms of the dimensions of the apparatus to be constructed.

In Captain Marryatt's novel "Poor Jack," there is a conversation between one of his beloved tars and a French sailor. "I asked him what he called the mizzen-mast," says the English boy, "and he told me the mar-dartymarng. How is it possible to work a ship in such a lingo?" "Quite unpossible," says Ben. Much like this of the poor sailor must have been the attitude of Kapp—himself no great mathematician—when he first tried to "work the ship" from the lingo of the physicists. "Quite unpossible" he found it; no ship could be worked in such a lingo. But that which was not "unpossible" was to interpret the said lingo in terms and language with which the engineer was already familiar. And this he set himself to do with intense and characteristic earnestness. Fully cognizant of the fact that all engineering is a matter of intelligent compromise, we watch him tossing carelessly aside useless mathematical refinements, and seizing with uncanny certainty upon those essentials which lie at the very centre and heart of the matter. "All very well," he seems to say, "for Maxwell and his disciples to express the behaviour of a transformer in terms of L and M, but what in stern utilitarian practice must the values of L and M be, and how are these related to the actual number of real cubic inches of metal from which the transformer must in fact be made?" These, and matters like these, were to Kapp the very essence of electrical engineering, and he set himself first to find the essential relationships, then to put them into practice, and finally, by teaching and writing—what I have called preaching the gospel—to hand them on freely and ungrudgingly to whomsoever would listen. He crystallized diaphanous and filmy formulæ into very visible, tangible and robust machines, capable of transmuting day and night the power of many horses into the new manifestation known as electricity; and he showed others how to do the same. This, as I understand it, is engineering and the teaching of engineering. First and last he was, according to my notion, an engineer.

Into the dissemination of this gospel Kapp put all his life and heart, working without stint early and late if so be he might predict more certainly the behaviour of a machine, or elucidate one point to an earnest student. To do this work he wore himself slowly out as the years went by, endowing thereby some of his students, his books and his inventions, with his own life; in virtue of which that part of his work must and will continue to have vitality, vigour and real meaning, for us and for others long after us. He was, as I said, an engineer; more than that—a pioneer—one who, having with whatsoever difficulty cut his little path through a thick jungle, did not hesitate to show it to others.

That the University of Birmingham did not benefit by the best of him as teacher is certain enough; how could it, when he was already 53 years old before he entered upon his career there? But if any would know what he could appear to a student, let them read the words of B. A. Behrend in his work on the "Induction Motor": "To my friend and teacher, Mr. Gisbert Kapp, I inscribe this work," he writes; and again, "the following presentation by Mr. Gisbert Kapp . . . is reprinted from his book . . . because it is the clearest and most concise logical evolution of the principles underlying the theory." And yet again, "it will repay the student to go over Mr. Kapp's presentation of the subject . . . after having become thoroughly familiar with this extract from the work of a master of the art of exposition." This is high praise from an old student. Would that all of us who are teachers or writers might deserve a like encomium.

"His contributions to the Proceedings of the Institution of Electrical Engineers were always highly valued," says Mr. Weekes in the *Electrical Review*. True enough; and his presence among us as a member of this Centre was highly valued also. We do not sit with engineer-pioneers and great teachers every day. Pioneering is apt in every direction to become more and more an exhausted occupation as the years proceed; the widening of the path, and the duty of making the crooked straight and the rough places plain, taking its place. This is the work for us—the successors of Kapp and his like. Let us see to it that it be done with humility, honesty and sincerity, worthy of the best work of the pioneer. And as we do it let us think sometimes of those who, with great labour and many heart-searchings, first trod that way; and let us remember especially him who often met us here without egoism or formality, and to whom to-night we bid a formal adieu, standing for one moment in silence, to mark our respect for his work and his worth.

II. Of the Institution.

The Institution has become the Chartered Institute. It has for the moment reached the goal of its ambition. All honour to those through whose self-sacrificing labours this result has been achieved! More still; the Institution has achieved popularity with the profession; has become indeed the nucleus and life centre thereof, insomuch that affiliation with it in some degree has become a necessity, and membership of it a hall-mark. There are more than 10 000 members, and the net increase in this great number was for the year nearly 9 per cent.

All this is a very visible indication of life and prosperity, which, with an income of more than £30 000 per annum, has the ability to be a great power and influence in the world if administered with wisdom and judgment, and if continually vitalized by that personal sacrifice of which I have already spoken. But whosoever reads history will find that all great collective endeavours, whether Empires, Industries or Institutions, do, at the very moment when they are greatest, and even because of that greatness, contain the germ of the disease which ultimately leads to their deterioration and decay.

It behoves us, therefore, at this time specially, to search carefully the body politic of our Institution for indications of the presence of any such undesirable microbe. Let us consider whether wisdom and judgment are being exercised in the administration of our affairs, and whether that life-stream of individual sacrifice is being poured unceasingly into the arteries of our undertaking, without which progress will cease and the body begin to waste.

We remark here that Presidents and Councils, not less than Kings and Cabinets, are nominally ministers —servants, that is—and should intrinsically be such, called and chosen on account of their wisdom, to express the best thought and intention of the community, and to carry these into effect. If President and Council do wrong, the responsibility is general, and rests not upon the executive alone. It is for the electors to get the best and wisest elected in whatsoever way they can, and summarily to eject any whose service they discover to be disservice. Moreover, if any man seek office openly or clandestinely, that man is, in my judgment, *ipso facto* unfit for office, as having no proper appreciation of the responsibilities whereunto he is called. Nomination, voting, and the method of election, are therefore serious privileges, far too lightly esteemed among us. No pains are taken by our members generally, to select, nominate, and elect those to whom they wish to entrust their affairs, either in the local committees or in the general Council; nor when the time of voting arrives is the return of voting papers at all representative. Too much trouble, it would seem, is involved in the thinking out of what we wish to get done, how it is to be carried out, and who are the best men among us to get it done. This is not the life-giving spirit of sacrifice. This is the microbe of utter indifference, which has a hold already in us as individual members, and through us is affecting the whole Institution. It is the mild form of a very insidious disease, apparent as one of the prevailing causes of the downfall of many institutions greater than ours. Its root and first manifestation is in the individual member, and with him lies the cure. The Council may do—does in fact—much to stimulate interest in itself and its doings; but this alone will not suffice as a cure—it is only a tonic. It is a question of conscience for each member to see to it that he votes for no man of whom he knows nothing, or of whom it may be said that he acts specifically for some "interest."

That the spirit of life-giving sacrifice is alive in the Institution is, however, apparent from the Annual Report of the Council. Some twenty-five voluntary committees, holding nearly 400 meetings in the year, bear eloquent testimony to this; to say nothing of the forty bodies upon which nominees of the Institution serve. Here is time to the value of thousands of pounds per annum in hard cash given most willingly; and to this not inconsiderable amount much might be added of time given by referees and others in divers unnamed ways.

Yet while thus joyfully admitting such good evidence of life, it is still incumbent on us to ask to what purpose this life is directed, what motive lies behind its manifestations, to be clear in our minds as to the road we are choosing and whither it leads. If we look back over the past twenty years, we find a vast extension of the activities of the Institution. It is a matter of no small interest to con old numbers of the *Journal*, and remark how this and that professor was asked, from time to time, to provide at the eleventh hour a paper or subject for discussion; failing which there would have been no meeting at all. The Institution in those days encouraged and recorded the knowledge of electrical engineering, and did little else. Its activities outside London were negligible. Now, like a huge Briareus, it spreads its hundred arms all over the world, embracing all manner of subjects, from wiring rules to German reparation payments. The growth has passed unmarked, because so gradual. But while thus extending our activities, let us never forget the lofty objects for which the Institution was founded, lest we fall into the position of a mere trade-defence organization. There is need for this warning! Has the Institution any call to deal with German reparation payments, E.P.E.A., and such like semi-political trade-guild work? Politics are no concern of ours, I think, and can only lead to diffusion of energy better employed in other ways; it is but a small step from reparation payments to questions of tariffs. Keep clear of politics, I say. Better, far better, to maintain and extend our original and highly successful expansion, resulting in the system of Local Centres. Has not the real growth and success of the Institution been due to this wise move more than to any other? Listen to the bitter complaints of the provincial members of the Institution of Mechanical Engineers; and remark how they, as well as the Civil Engineers, are being obliged to follow our example in this matter. I can never sufficiently admire the foresight and genius of those who first established our Local Centres.

If, however, in the matter of local devolution we have been able to set the fashion for other Institutions, there still remains the question of their kinship with us, which at the present time fills me with much misgiving. Their number increases alarmingly, and one's list of subscriptions becomes a matter of importance. Besides the three major Institutions, we have the Iron and Steel Institute, the Junior Engineers, the Society of Civil and Mechanical Engineers, the Association of Mining Electrical Engineers, the Faraday Society, the Electrochemical Society, and I know not how many others. Each has its own office and staff, its own *Journal* and meetings and subscription. Curious, too, how a given subject will go the round of them with repetition of discussion *ad nauseam*, and monstrous accumulation of redundant printing. Clearly the matter cannot be left where it is; co-operation or affiliation must be compassed in some manner, or we shall be crushed under the mass of printed stuff waiting to be read.

But how to do it? That is the question. The Institution of Civil Engineers has called a conference on the subject and is apparently in labour. Will it bring forth anything? If not, the Institution of Electrical Engineers should and must take it up, as being concerned in the matter more vitally than any other. But we know the difficulties. Three great Institutions, each with its own palace, and all within one square mile! Did man ever hear the like of it? More than half a million sterling spent by engineers on three piles of bricks and mortar in the neighbourhood of Westminster, and nothing—not so much as would shelter three blind mice—provided in Manchester, or Liverpool, or Leeds, or Sheffield, or Birmingham, or Bristol, or Glasgow, or anywhere where engineers live and move and do verily make engines! All the accom-

modation put near Westminster, where some plans are indeed made, but virtually no engineering is actually done! Three palaces, I say, three libraries, containing largely the same books, and three secretariats with all their appurtenances and vested interests! Which is going to give way? I confess that I have no panacea to offer as an instantaneous cure for these evils. Nay, more; to put forward cures is not really my business. It is my business to do what in me lies to get intrinsic wisdom on to the Council by means of my vote, and then from time to time, as now, to point out such defects as appear to me to await the attention of intrinsic wisdom. Yet lest my comments should appear to be merely destructive, I will presently put forward with great submission five suggestions as a basis for the better administration of our affairs.

In the meantime, let us lay this to heart, namely, that if we had known our business the situation had never been so bad as it is. We were the last to buy a building, and with us also lies the responsibility for the existence of at least three of the societies that I have named. For consider what might have been done with the £73 000 spent upon our London palace. In 1913, Manchester engineers equipped a whole club for £2 000, paying an annual rental of £600. If in London we had been content to limit our expenditure by a judicious arrangement with one of the other great Institutions, increasing thereby the present wretched load factor on their buildings, there might have existed by now at least an Institution library and reading-room in every important centre in the Kingdom. What a spread of fellowship would this have produced among us; what opportunities for intercourse, exchange of ideas and for reading! Contrast it, if you have imagination enough, with London and its maximum of 1 651 attendances in the library per annum, 5 per day! There would have been nothing like it in the world!

Comparison of three Institutions, 1921.

	Civils	Mechanicals	Electricals	Total
Capital expended on land and buildings in London ..	£ 352 000	£ 100 800	£ 73 000	£ 525 800
Annual subscriptions	24 100	22 260	28 360	74 720

Approximate Annual Costs of London Buildings.

	Civils	Mechanicals	Electricals	Total
Rents, rates and establishment charges	£ 11 300	£ 5 300	£ 5 600	£ 22 200
Interest on mortgages and loans	1 044	1 361	1 243	3 648
Interest on balance of capital at 5 per cent *less* rents received	15 900	3 680	1 900	21 480
Total	£28 244	£10 341	£8 743	£47 328

Interesting Annual Items.

	Civils	Mechanicals	Electricals	Total
Salaries and wages, 1921	£ 11 000	£ 9 450	£ 9 400	£ 29 850
Salaries and wages, 1914	7 650	4 200	3 330	15 180
Local Centres	940	390	2 370	3 700
Research	—	790	218	1 008

Such a combination of interests might have led, nay might still lead, to other advantages, of which not the least would be the reduction of our annual charges. Our subscriptions amount to £28 000, of which £11 000 is spent upon management. Now to light, heat, and pay the ground rent, rates and taxes, on our London building costs £7 000 per annum, or a quarter of all our subscriptions, without including interest on mortgages and on the capital sum invested. If we add these amounts and allow for the rents received we find that to maintain our dignity and prestige we are content to pay not less than £18 000 every year. Our idea of the value of the papers we receive as shown by the premiums awarded is £208,

and our contributions to research amount to £218! Does this indeed represent the relative importance of these items? And are not our colleagues of the other Institutions in a worse case? Look at the table which I have given on page 139, and see whether such a scheme of co-operation as I have suggested ought to be regarded as impossible; ought not rather to be regarded as the one thing necessary, and therefore most possible and urgent; the only way, in fact, to achieve further territorial expansion, and adequately to develop the Students' Sections.

I will not harrow you by attempting a picture of what might have been had the Civil Engineers not been so very uncivil to George Stephenson, nor describe the Great Institution of Engineers that then had been possible. I will not suggest the multifarious activities in which our own Institution might more profitably be engaged; not at least until some of those 25 committees have got their work finished and themselves disbanded. I desire to simplify the issues rather than to make them more complex. There are indeed many suggestions that I might make, but we have reached our conclusions and must conclude.

Here then led me refer to the table containing some comparative data of the three greater Engineering Institutions from which my statements may be checked, wherefrom also some grain of comfort is plainly derivable. For while our capital commitments are seen therein to be the smallest, our income from subscriptions is also seen to be the largest; and while our contributions to local Centres are indeed nothing to boast of, they do amount to nearly twice those of our two sisters taken together. These are signs of grace upon which we are entitled to look hopefully. But far better were it to ignore them altogether than to blind our eyes to the microbes of the diseases which I have diagnosed as existing in our system, and for whose extermination I have now the temerity to put forward the following prescription:—

(1) Whole-hearted devotion on the part of the rank and file to the objects for which the Institution was established; more interest in the discussions, and in the selection and election of representatives on the Committees and Council. It would be well if all would read over the objects, as stated in the Memorandum of Association, at least once a session.

(2) The elimination from our activities of any concern with political or semi-political movements, industrial relationships, or trade-guild propaganda.

(3) The encouragement and extension of the Local Centres, and a more generous treatment of these financially. In particular, the reduction of expenses in London in so far as that is practicable, and the establishment of Institution accommodation and libraries in the provinces.

(4) Encouragement and more generous treatment of the Students' Sections.

(5) Co-operation and, if possible, fusion with other Engineering Institutions, ultimately to form one great English-speaking Institution of Engineers.

IRISH CENTRE: CHAIRMAN'S ADDRESS

By E. C. HANDCOCK, Member.

(*Address delivered at* DUBLIN, *26th October*, 1922.)

The subject of my Address is: "A Consideration of the Present and Immediate Future of the Irish Centre of the Institution and of the Electrical Industry of Our Country."

I propose first to touch briefly on two developments of engineering interest which have crystallized since our last session, and which may, I hope, be described as being on the border of fact, namely, the advent of two much-talked-of water-power schemes and wireless broadcasting; and then to consider some questions intimately affecting this Centre, and finally the possibilities of an electrical manufacturing industry in our country.

RIVER BANN SCHEME.

The River Bann will, from present appearances, be the first of our Irish rivers to be harnessed on a substantial scale for the generation of electricity. A strong syndicate has this electrification in hand, and hopes to get a Bill through the Parliament of Northern Ireland in the immediate future. We can be certain that, as soon as the legal path is cleared, no time will be lost in converting this hydraulic energy for the service of the factories, villages and towns along the banks of the Bann.

RIVER LIFFEY SCHEME.

The harnessing of the Liffey for electric power supply has been a subject of much discussion. This Centre and other engineering societies have discussed its possibilities. It is well known that they have been actively investigated for some time past, and we are now awaiting the final recommendations.

Assuming these recommendations to be favourable, it is to be hoped that the decisions covering the method of finance and control will be taken and published without delay. These decisions will be very important, as they will form a precedent for other schemes. Seeing that the water power is a national resource, I hope that national money resources will, at least to some extent, be applied to its development, giving the principal consumers (in this particular case Dublin Corporation would of course be the largest) an important voice in the control.

It is reasonable to assume that in some 12 to 15 years, after a considerable portion of the capital has been repaid, this scheme could prove a valuable source of revenue to the nation.

I can imagine the control board of this scheme being of further service by forming a common centre where the different electricity supply authorities in the Dublin area might meet and agree to mutually advantageous arrangements for the distribution of electrical power.

WIRELESS.

Wireless application is at present being hampered by restrictions foreign to its technical side, but it is developing and increasing in vitality out of sight, so that immediately these restrictions are withdrawn it will spring up with just so much the greater vigour. This latest branch of our profession is one that will appeal more perfectly to the community than perhaps any other section of electrical work. It brings with it not only a young and enthusiastic set of men in its service, but also a vast number of the public, anxious to know something of the use of this truly uncanny development. It may be mentioned that the Wireless Exhibition held in London at the beginning of this month was visited by over 25 000 people.

It largely rests with us as to whether we retain a directing control in the formation of the technical rules and regulations in connection with wireless services. To do this we must actively interest ourselves in this new science, co-operate with those specializing in it, help them from our wider experience in electrical matters, and especially give these young men facilities for meetings and papers on their own subject.

I now come to a matter of the utmost importance: How are the recent changes of Government in Ireland going to affect this Centre and our profession? In the following remarks it should be clearly understood that I am referring to the Irish Free State only, and that any suggestions or opinions put forward are of course purely personal.

To try to outline the effect of the change of Government, the steps to be taken in the immediate future, and the general tendency along which this Centre should travel, will necessitate going over matters already well-known to all. It is, however, desirable to re-state our position.

THE INSTITUTION.

The Institution of Electrical Engineers is rightly called the mother of electrical engineering societies. We belong to the youngest of the professions. Nevertheless, the membership of the Institution is well over 10 000. The standing of its members is acknowledged in every part of the world to be of the highest. This is of exceeding personal importance to all of us, as we electrical engineers in Ireland, as elsewhere, are liable to go abroad.

The record of our Institution is practically that of electricity. Ireland has given it many of its most prominent men, from Lord Kelvin to that of our present President (Mr. F. Gill) who is not only a Dublin man but also one of the original members of this Centre.

The Standard Rules accepted throughout our country for electrical work are those of this Institution. The development of our profession is so rapid, and improvements take place so quickly, that the Institution has had to form many standing Committees for the effective control of these developments. Their results and records will be of inestimable value to us.

Irish Centre.

The Irish Centre consists, for all practical purposes, of the electrical engineers of experience and authority in Ireland. It comprises electrical engineers of all branches of electrical work except one (at least as far as the Irish Free State is concerned), and that one is the industrial or manufacturing side. Our number is small, being 148 for the whole of Ireland, but I venture to say that no similar number of men in Ireland have the control of such power, literally and figuratively, in their hands. The community rely on this small body of men for its supply of electricity for lighting, industrial power, tramways, telephones, telegraphs, railway signalling, etc.; in fact there is not a profession or trade that is not in a major or minor degree applying electricity to its service.

I say that it is a good thing for the community that we have a due sense of our responsibility.

There are one or two points that it is desirable to touch on for the welfare of this Centre. The first is the question of a home and an address. At present we have no home. I should be satisfied if we had one room of any kind for the housing of our library, and I am quite confident that with a place to keep our possessions, those possessions would grow. Having a room we could build up that very desirable thing, a good up-to-date reference library.

This question is also of importance to our Graduates and Students. We are anxious to increase the number of these and they would feel more at home and free from restraint when meeting in a room belonging to the Institution.

It is very desirable that all electrical engineering students in our technical colleges should know the advantages of belonging to the Institution. They should automatically join as Students when starting the last year of their college courses. The younger men ought to understand that in a few years' time they will not be accepted as qualified electrical engineers unless they belong to the Institution, any more than a man is accepted as a chartered accountant unless he has qualified and passed the examinations of his Association.

I should also like to say a few words with regard to Associates. It is not sufficiently well known among the public that an Associate of the Institution, by the mere fact of being an Associate, admits that he is not a professional electrical engineer. This class is created for, and open to, all members of other professions whose admission would conduce to the interests of the Institution. I cannot help feeling that there are many men eminent in other professions in Ireland whose admission would be mutually advantageous.

On the one hand we should learn from them their very specialized applications of electricity, and, on the other hand, once we knew their exact requirements we could lay ourselves out to give them perhaps something better in the way of electrical apparatus than they have at present. Contact is, however, necessary.

Effect of Change of Government.

Having dealt with these minor but important matters I come to the broad question as to how the change of Government is going to affect this Centre and our profession as a whole.

To begin with, it is necessary to realize clearly that we are, and shall be for some time, carrying on with electrical rules, regulations and laws more or less in a state of suspense. This means, as I see it, that our existing rules are replaced by blank sheets of paper. *Inter alia* I would remark that in the past we have accepted all these various rules, regulations and laws controlling our profession, which others have provided for us, without, I fear, any appreciation of the labour and trouble that the compilation of these has meant.

Now, bluntly, the question is whether we are going to help to rewrite those blank pages. There are two paths open to the Irish Centre :—

One, that of apathy, allowing others to accept the responsibility. If we remain apathetic, can we expect to be taken seriously if we protest against any technical rules or regulations of which we disapprove ?

The second, and to me the only possible path, will be to accept manfully our responsibility and, further, to make it clear to all concerned that our members interested cannot reasonably be expected to carry out and be responsible for the application of technical rules and regulations governing our profession unless the Irish Centre has a voice in their framing.

I pointed out before that we had a sense of responsibility to the community, but at the same time we are aware of our value as well as our duty.

Responsibility reflects responsibility. Accordingly, those acting for the community will no doubt realize their responsibility to our profession and appreciate the advantage of having in existence the Irish Centre of this Institution to co-operate with in the re-affirming, revising, or recasting of our highly technical rules and regulations, making them, where necessary, more suitable to our local requirements. My remarks are purely personal, but I have no hesitation in affirming that if and when called upon by those in authority to do this work, this Centre will give of its best for this duty.

It will be absolutely necessary for us to rise to this opportunity, for which we shall require all the experience, foresight, and wisdom possible.

It means the framing of rules and regulations affecting generations to come. It will be of the utmost importance not to fall into the mistakes made by other countries in making the framework of their rules too rigid. The framework must be made so as to be adjustable from time to time, to give flexible control, regulation and standardization. In this connection I would point out one very important point where the future will be very different from the past, and the sooner it is appreciated by all concerned the better. Regulations will have to be lived up to. For instance, there will be no

more self-constituted electric supply authorities without authority.

The change of Government is, in my opinion, going to be beneficial to this Centre in the ratio that we accept responsibility, and work, and use our influence for the good of our profession and the community.

Before leaving this subject, and in the hope that these few words may reach the proper quarter, I repeat the great desirability, nay necessity, for a definite understanding between this Centre and the Government Department responsible for the making of technical regulations governing the generation and supply of electricity, or in connection with electrical apparatus.

Electrical Manufacturing in Ireland.

The other question with which I wish to deal to-night is one on which I feel strongly. It is that of the possibility of electrical manufacture in the Irish Free State. After writing that last sentence I sat and looked at its grotesqueness. A country with $3\frac{1}{4}$ million inhabitants, setting up its own Government with an Army and other Government Departments, and yet I have to write "possibility of manufacturing" in regard to the most necessary and vital, most progressive and most rapidly developing of all industries. Yet it is perfectly true; for, with the possible exception of one small company, I know of nobody attempting electrical manufacture in this country.

This is a most unhealthy state of affairs, not only for our profession but also for the country. It is an explanation of the meagreness of our membership as a whole, and especially of our Graduate and Student sections.

What is the reason for this state of affairs? I have often asked this question but have never got a satisfactory reply, so I am quite certain that I shall not satisfy you by a definite statement.

I shall, however, treat it indirectly by asking if we electrical engineers have used our influence to create an electrical industry. We, who are familiar with electrical apparatus and know that it is not so difficult to manufacture or so mysterious as the public may think, have we endeavoured to interest capital? Or have we taken up the attitude that it is impossible to make anything in Ireland?

I definitely maintain that those of us who are in a position to influence the investing of capital in our profession should do so, in addition to giving all possible support to a home industry, contingent on that industry showing that it is seriously endeavouring not to obtain a high price for an inferior article. It is regrettable that many people have taken up the attitude that we are unable to manufacture. The very first thing necessary is to get rid of that frame of mind. It does not matter how small the article is to start with, but let people get interested in production and the good work would go on.

Another frequent answer is that there is not the demand in this country. There is not, of course the demand for the production of turbo-alternators and large machines, but there are some $3\frac{1}{4}$ millions of people in the Irish Free State, and if the home market alone cannot support a reasonably good electrical manufacturing industry, then this is only due to some artificial cause which must be got rid of. But there is no such reason.

Let us take some other European countries. The population of Denmark is $2\frac{3}{4}$ millions, Norway $2\frac{1}{2}$, Switzerland $3\frac{1}{2}$, and, as is well known, those countries manufacture electrical apparatus extensively, not only for their own purposes but actually to export a considerable quantity.

Canada is in a very similar condition to ours, in that she is next door to a country with immense production facilities, a country continually looking out for markets for her products. In 1904 the population of Canada was $5\frac{1}{2}$ millions. I take that date, partly because her population was much smaller than at present, and partly because I had an opportunity to see some of her electrical facilities.

At that time the Canadian General Electric Company had a factory occupying 40 acres, where they turned out practically everything electrical. The Canadian Westinghouse Company had a similar organization, and in addition there were numerous small factories, all forming a young and vitally alive industry.

The High Commissioner for the Commonwealth of Australia has kindly sent me the following particulars of what is being done there.

Number of Manufacturers of Electrical Apparatus.

	New South Wales	Victoria	South Australia	Western Australia	Queensland	Tasmania
Population (1911)	1 650 000	1 315 000	408 000	282 000	605 000	191 000
Motors	12	18	1	2	—	—
Starters	8	8	1	—	—	—
Switchboards	17	15	1	—	4	—
Switchgear	7	3	—	—	—	—
Transformers	3	10	—	—	—	—
Travelling cranes	3	1	—	—	—	—
Instruments	8	7	—	—	—	—
Machinery	4	5	—	1	—	—
Fittings	14	13	1	2	1	1

These figures taken in proportion to the population show what can be done. Compare them with the Irish Free State.

The change of Government is going to give a strong inducement that was previously absent. Government Departments are now in a position to place contracts at home for quantities which will ensure a manufacturer having a reasonable and continuous output from the start. This will enable him to produce at reasonable prices whilst developing his business along the usual trade channels.

Without such contracts it is difficult to face competition with manufacturers already established and holding such contracts from their own Governments.

When speaking of electrical manufacturing it should not be overlooked that it is in a very large degree mechanical work, and work that a number of our well-equipped mechanical workshops in Dublin could undertake if they would only look into it and add an electrical engineer to their staff to ensure that the design and finished product were in accordance with electrical requirements.

PATENTS.

The question of patents is a delicate one. It will, however, be disappointing if the practice of other countries is not followed in making it necessary for patentees to manufacture in our country in order to retain their privileges. In this connection it might be worth while putting forward a suggestion as to the possibility of eventually establishing a permanent Inventions Bureau following the practice of Great Britain during the European War.

RESEARCH.

This automatically brings me to the question of research work. Important developments are sometimes the result of a "brain wave" but more generally are the cumulative effect of patient research work. Research work costs money, and the only method by which it can be undertaken is by Government aid, or where huge trusts or combines are in such a strong financial position that they can put on one side an allowance for this work. Having no electrical manufacturers, much less combines, the only alternative is Government aid.

Dr. Eyre, Director of the Linen Research Institute installed outside Belfast, has kindly sent me particulars of this Institute and its method of support.

It fits into the comprehensive scheme that each industry is made responsible for its own research work. The different companies subscribe annually an amount corresponding to their capital. For example, in the linen industry a company with a capital of £17 000 subscribes £10; from £17 000 to £26 000 the subscription is £15, and so on, the Government voting a grant which is allocated pro rata on the amount contributed by the industry. This is an admirable scheme but impracticable for us. I would suggest that there should be a laboratory capable of research work at each of our electrical engineering technical colleges. Further, that one of the staff in each college should be appointed on account of his outstanding merit on research work. The results of such work should be given to our own manufacturers in the first instance. Where such results were patentable the resulting fees (due allowances being made to the inventor) should in due time help to support this work.

What I call "educational engineers" might be termed "manufacturers" from one point of view, in that they are taking raw material (our young manhood), representing the most vital part of the capital of the country, increasing its value by a technical training, and then exporting it abroad, for the simple reason that we have no electrical industry to absorb our young electrical engineers.

TECHNICAL EDUCATION.

The apparent situation is that tens of thousands of pounds of national money is annually expended in our technical colleges, covering the first definite step in the education of our young electrical engineers, and for the second and nationally more important step of consolidating their college training in a manufacturing works neither national nor private capital has expended a penny. This second step is nationally more important, as in order to get this experience these young men leave the country and seldom return. If one-tenth of this money had been available for commerical enterprise it would not be a case of writing as to the possibility of an electrical industry.

Do not think that I would wish to suggest the reduction of the grants for technical education. The remedy does not lie in this, but in creating and developing work at home so that those young men can make a livelihood and devote their energies to their profession without going abroad, and I hope that in the near future this will be possible.

The term "educational engineers" has been used in order to get away from the more academical term of "professor." Our educational engineers should not have the idea that they are simply responsible for getting into the heads of their students sufficient knowledge of a technical nature to enable a reasonable percentage of them to pass their final examinations. Those in charge of our colleges should remember that they are part of the electrical industry of this country and that they are in their positions for the sole purpose of furthering the interests of this industry as a whole. It is true that their primary concern is to educate our young manhood, but it is also important for them to keep in contact with the operating side of their profession, placing themselves and their laboratories at the service of the industry. This would automatically mean that they could place their students along lines of maximum efficiency.

This Centre is common ground for all the branches of our profession. It would be gratifying to see it made use of by the interested parties for the purpose of bringing about a research arrangement as outlined above, and for bringing our technical colleges into more intimate relation with our electrical industries in the future.

We are a relatively small community, and are at a most critical period in our economic development. We are starting peculiarly free from precedent and vested

rights. This is a combination that, given team work, makes for efficiency. In the past we have allowed our individuality to overrun our team work, hence our more or less watertight compartments.

Co-operation.

It is most desirable that everybody interested in electricity, whether he be an electrical engineer, a member of the Government, or a shareholder in a village electric lighting company, should co-operate through his respective association or institution so that electrical engineering, acting as a living whole, may most efficiently play the part in building up our country that it has in others. This part is of the greatest national importance, entering into the health and well-being, industrial and physical, of the community as a whole.

If my remarks to-night have had any effect in bringing home to this Centre our responsibilities in the immediate future, I shall be satisfied. At the same time I sincerely trust that some of the suggestions put forward will be such as to stimulate thought.

In conclusion, I hope that the vigour of this Centre, which has steadily increased under the energetic and capable direction of our last three Chairmen, Messrs. R. Tanham, A. G. Bruty, and R. N. Eaton, will be made full use of for the control, development and efficiency of that most vital, rapidly growing, and important profession to our country, the profession of electrical engineering.

NORTH-WESTERN CENTRE : CHAIRMAN'S ADDRESS

By A. S. Barnard, Member.

(*Address delivered at* Manchester, *14th November*, 1922.)

I should first like to draw attention to the step taken last year, largely on the initiative of our new Hon. Secretary, Mr. A. B. Mallinson, and Mr. W. A. Coates, in the inauguration of Informal Meetings. From these meetings the reporter is rigorously excluded, and, judging by the success attained last year, I think we may look forward to their proving a most useful and interesting feature of the present session.

The range of activities covered by our membership is now so extraordinarily diverse that there are a host of comparatively small matters—which might be called side-lines of electrical engineering—which are of interest to members, but which very possibly do not warrant the devotion of a whole evening's debate to the one subject. The informal meeting affords an opportunity for arranging short discussions to deal briefly with two or three such subjects at one meeting.

When it is remembered that electrical engineering in its widest sense has now a foothold in almost every human activity, it becomes obvious that, important as are the questions of cheap generation and distribution of electricity, these are not the only matters which the Institution must consider, or in which alone it will be looked to by its members for guidance. For example, in the electrical equipment of ships, or of railway rolling stock; the use of electricity in surgery and therapeutics; electricity in mining, agriculture, textile mills, or chemical industries; and wireless telegraphy and telephony, there are very many members of the Institution who are interested and who could interest us in these and similar applications of electrical engineering. I should like to see some of our informal meetings devoted to discussions not only on theory and design, but also on a working experience in many of the lesser side-lines of electrical engineering.

I propose to deal very briefly with some of these minor subjects which I have described as side-lines.

Why is it that we still have gas-lighted passenger trains in Great Britain? Have we as an Institution ever taken any steps to develop the use of electricity in this direction? Surely there have been sufficient examples of the danger to life from gas-lighted coaches to afford us a text for a strenuous campaign in favour of the only safe illuminant. Train lighting by electricity remains, however, a comparative side-line in the hands of a few, and, so far as I am aware, it is not even necessarily installed in the new rolling stock built to-day. The obvious advantage of being able to light up a train as it enters a tunnel is so frequently exemplified in the police courts that one wonders why it is not made compulsory.

The subjects of wiring for power in works and factories, and the kindred one of domestic electric lighting, must receive attention at the hands of the Institution if we are really concerned in the development of the industry on the right lines. The final authority in these matters is the consumer who pays the bill. If wiring is made too expensive by elaborate specifications and regulations, less wiring will be done, for the consumer will object to the cost. If on the other hand we tolerate inefficient and shoddy wiring, there will be little use in building super-power stations and offering cheap current to a man who experiences trouble and expense through the inefficiency of the installation on his own premises. The wiring contractors are probably in more direct touch with the consumer than any other members of

the electrical industry, and for that reason, if for no other, they have a big responsibility in the matter of wiring practice. They will help themselves and the whole industry if they will discuss their difficulties and troubles with the Institution as freely as do plant manufacturers and central station engineers.

This session will, I hope, see some attention paid to the important work that is being done by the electrical engineer in the collieries. My earliest experience of electrical work was gained in the collieries of South Wales, and I still remember the joy of switching on new lights underground, or starting up a motor-driven pump by the light of a Davy lamp. I am afraid that the immunity from electrical disaster of those early installations must be ascribed to something else than the excellence of the work which we carried out, or of the machinery we installed, for I have recollections of old Gramme machines with open (and by no means sparkless) commutators, and cables, switches and accessories that would prove an endless source of worry to the present-day mining engineer. Electricity in mines has now gone far beyond the experimental stage, but I am sure that there are yet many problems of great interest which could with advantage be discussed by this Institution—problems ranging from the heavy engineering of haulage and winding to the relatively small but important question of the design of a miner's portable lamp.

Electricity in agriculture is a side-line which perhaps may not be expected to be of particular interest to this Centre, though it is conceivable that if we devoted more attention to the subject of smoke abatement we might develop a more personal interest in this very fascinating application of electricity. As things are, the smoke-clouds of Manchester and the neighbouring towns are responsible for a tremendous waste of energy on the part of farmers and gardeners who plant hopefully, and reap occasionally. When we reach the All-Electric Age, and when open domestic fireplaces and smoke-making locomotives are things of the past, we may hope for a great improvement in agriculture.

There is one branch of agriculture largely practised in our area which seems to me to offer a promising field for research. If we could devise an electrical treatment of seed-potatoes that would render the crop immune from wart disease, we should confer an immense boon on the potato growers of Lancashire, and earn the gratitude of thousands of allotment holders. You may say that this is not electrical engineering, but I claim that it is a proper matter for consideration by electrical engineers, and I need only point to the results obtained in Herefordshire through interesting the farmers in electricity, to show what a bearing these side-lines can have on the larger problems of public electricity supply.

We in this country are too prone to leave it to others to show us what can be done. We established electricity supply stations to supply electric light. The supply of current for power purposes was an experiment, and, in the view of very many people, not too hopeful a one. Electric trams were said to be working successfully in America, and gradually we learned to tolerate the overhead trolley wires in our cities. Are we to wait until the whole of the American railways are electrified before we really tackle the problem of main-line electrification in Great Britain? We know that the electrification of the railways will benefit the nation; we know that sooner or later it will be carried out; surely, therefore, we should educate public opinion in the matter, and make the advantages so clear to the ordinary traveller by train that he will insist on the electrification of railways. I think there can be no doubt that the matter would advance more rapidly if the electrical engineers of this country would make a decided and authoritative pronouncement as to what should be the system to be adopted ultimately throughout the main lines of the British railways. I think also that the Electrical Development Association might usefully devote some of its energy and resources to cultivating public opinion and creating a more insistent demand for this reform.

Legitimate advertising and publicity are forces which we can no longer ignore, and the work of the Electrical Development Association is a side-line which will require more and more attention at the hands of the Institution.

I look upon the storage-battery industry in which I spend my time as being another of these side-lines. There was a time when the central station for the supply of electricity in a town consisted of one, two or three direct-current generators, driven by vertical steam engines, usually of the high-speed, single-acting type. In those days the storage battery was an essential part of the scheme, making for economy by enabling the running plant to be shut down for several hours in the night, and even over the whole of the week-end. These early installations have been scrapped or superseded as the growth of the industry called for larger and more economical generating stations, and as the turbo-alternator was developed to meet that demand. In many instances, however, the original direct-current station has left a legacy in the form of a direct-current network of mains, to which are connected large numbers of consuming devices and installations designed for direct current alone. It happens, therefore that in many of our larger cities the densely loaded d.c. network survives in the heart of the important business area, whilst the outer manufacturing or residential areas are supplied by a.c. distributing mains. This, of course, leads to some complications and a measure of inefficiency, and the question arises as to whether there is any justification for the survival of these large d.c. networks. My own opinion is that a plebiscite of consumers would show an overwhelming majority of power users in favour of a.c. supply, but an equally overwhelming majority of private users, shopkeepers and residents, who would favour direct current. The exact reasons for this preference would take too long to discuss, but one of the justifications can be found in the possibility with direct current of holding a little in reserve in a way which is practically impossible with alternating current, depending as it does on running machinery and a constant supply of labour and fuel in the boiler house.

It is easy to ridicule the idea of using storage batteries to deal with the immense loads on the mains in a city like Manchester or Birmingham in the event of a

complete breakdown of the generating plant. It may be said that this risk is insured against by linking up with adjacent supply undertakings, and I grant that this does give a very real safeguard to the continuity of supply. At the same time, it must be remembered that the conditions which are temporarily upsetting the plant may be affecting other supply stations also. The fact remains that a few thousand kilowatts in a storage battery at a substation, instantly available and under direct control, may easily convert what would have been a serious interruption or curtailment of supply, into a slight irregularity which would pass unnoticed by the majority of consumers.

A year or two ago, when both labour and fuel conditions were at their worst, the peak-load supply apparently became a nightly difficulty in more than one large electricity undertaking. I was somewhat surprised to see how calmly the consumers accepted the dictum of the engineers and committees that the supply would be curtailed or restricted between certain hours, or as regards certain classes of consumer. Of course there are commercial limits to the value of storage, but I cannot help thinking that in the past some of the failures to meet obligations to the consumer have been due to an over-zeal for economy, rather than to that hoary scapegoat "The act of God." And what supply authority has really tested the commercial possibilities of storage?

When one examines the comparative statistics given in the *Electrical Times* and sees how very few of the public supply systems are working with a load factor of more than 25 per cent, one wonders what would be the effect on the average cost per unit if the load factor were brought up to unity, or even to 50 or 60 per cent. The figures of one large station are as follows:

Total units sold	137 000 000
Maximum demand	67 100 kW
Load factor	23·29 per cent
Total works cost	1·73d. per unit.

Is it not conceivable that with a really comprehensive system of storage, for example a system that would bring this load factor up to 50 or 60 per cent, the works cost could be brought down to 1·23d. per unit, with a gross saving of 137 000 000 half-pence per annum or, in round figures, £250 000 per annum? The maximum load of 67 000 kW may be regarded as plant having a capacity of 32 000 kW running at 50 per cent load factor, and a further 35 000 kW capacity running idle all the time. Storage that could take charge of 35 000 kW for, say, two hours per day would, in all probability, be amply sufficient to ensure that the running plant necessary to meet the maximum demand would work year in and year out at a load factor of 50 instead of 23·29 per cent. Battery substations to provide this storage would cost, so far as I have been able to ascertain, somewhere about £1 000 000, and there would be a problematical £250 000 per annum to pay for the capital and working expenses. I know that the idea will be scouted, but I submit that the question of storage is not generally treated seriously enough, or looked at with a sufficiently large and wide vision. A reserve of energy of 35 000 kW for two hours, or nearly 55 000 kW for one hour, is a consideration not to be ridiculed, even if the million-pound capital expenditure is a big sum, and even if the battery losses and maintenance costs would account for a large proportion of the £250 000 per annum that I have suggested might be saved by an improved load factor.

We have had in the past some very useful discussions on the subject of specifications and the work of the consulting electrical engineer, but I do not think that the last word has yet been said on that matter. The difficulty of drawing a specification which shall define while it does not exclude, seems to be insuperable, and is only equalled by the difficulty experienced by the contractor in gauging the exact percentage of deviation from the "letter" that will be accepted as still being in accordance with the "spirit" of the engineer's requirements. So long as the system of competitive tenders survives, the contractor is haunted by the knowledge that the quotation which, on being first read, shows the lowest figure as the "contract sum" has secured a psychological advantage over all others. Close investigation will often show that this is not really the cheapest tender, but the first impression has been created, and it requires an effort on the part of the consulting engineer to clear that impression away and secure equal consideration for the remaining tenders. Under these circumstances it is not surprising if, in tendering for, say, a ship, the contractor is tempted to omit the tar and thereby reduce his tender to a figure lower than his competitors'.

It is my conviction that the high standard of engineering work attained in our municipal power stations has been reached in spite of, and certainly not because of, our system of public invitation to tender; and now that there is a certain amount of standardization in prices for standard work, it calls not for less, but for greater care on the part of the consulting engineer to secure that his client shall obtain the best bargain.

Another matter which I think concerns us as an Institution, is the qualification of the electrical contractor who carries out the installation work in our houses and factories. I am well aware that this work of wiring is hedged around with regulations and rules, and quite frequently is inspected on behalf of a supply authority or insurance company. For all that, it is obvious that a certain amount of shoddy work is still being done, and shoddy work in wiring brings discredit on the electric lighting industry, and thereby on the whole electrical profession, more quickly almost than any other factor. I feel that until we evolve some system of national registration of electrical engineers we shall continue to expose a very vulnerable point in our armour to the attacks of those who work for immediate returns in hard cash, without regard to the effect of their work on the industry as a whole. Any such system would have to include the registration of master contractors as well as of wiremen and electrical mechanics. Were it merely a question of workmanship on the part of the wireman the matter might safely be left to the trade unions concerned and it would gradually right itself, but scamped work is as liable to originate in the office as it is to occur on the actual job. Furthermore, it is common knowledge that the electrical

contractor is often the customer's sole adviser and consultant, and, when it is remembered how largely electrical engineering is judged by the reliability of the light in the living room, it can be appreciated how much we, as an Institution, are concerned in the status of the wiring contractor.

I think that the electricity supply industry is to be congratulated on the thorough-going manner in which it has adopted the scheme of Whitley Councils. I am sure that this scheme will go a very long way towards stabilizing and consolidating the labour in this industry, where stability and continuity of service are matters of great value. I know from experience that the works committee can be a powerful agent for good in a factory, and I feel sure that the results that can be obtained by the open discussion of difficulties will be none the less marked in a supply undertaking. Certainly the managerial representatives on a works committee such as that in the factory with which I am associated find the time well spent, if it is only in their own education. I would urge employers of labour to trust the works committee more and more, remembering that responsibility begets a sense of responsibility, and trust engenders loyalty.

This principle might with advantage be extended in other directions and applied to the relations between buyers and consulting engineers on the one hand, and manufacturers and contractors on the other. I should say that the surest way to get scamped work from a contractor or manufacturer would be to let him think that you expected it. Treat him honourably, and expect him to treat you so, and the chances are that you will not be disappointed. In other words, when you are treated as a gentleman, you instinctively try to behave like one.

Our War Memorials have another function to which I should like to allude very briefly. They serve to emphasize our dependence on each other, and the uncertainty of accomplishment of our individual plans. In a large Institution such as ours there are inevitably many members whose plans will be upset and who will fall by the wayside. We are all aware of this, but I think we do not all fully appreciate the significance of the facts in relation to ourselves. If we did I feel that there would be a greater response to the appeal for regular annual subscriptions to the Institution Benevolent Fund, the only limitation to which at present is the fact that its power for good is at present limited only by the inadequacy of its material resources.

In conclusion I wish to direct your attention to an event which I hope will be a source of great pleasure to us all. In June next the Institution will visit the North-Western Centre for its Summer Meeting. Friends from all over the country will be coming to see what we have to show them of electrical and scientific interest, and it will be our very pleasant duty to make their visit as enjoyable as possible. As a Centre embracing Manchester, Liverpool and North Wales we have unrivalled opportunities, and your Committee is determined to make the occasion a memorable one. I am sure that in so doing we shall have the whole-hearted support of every member of this Centre.

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By A. S. HAMPTON, Member.

THE ECONOMIC ASPECT OF RAILWAY ELECTRIFICATION.

(*Address delivered at* GLASGOW, *14th November*, 1922.)

Experience gained steadily confirms the high value of the results obtained from the electrification of suitable railway sections, and but for the present financial difficulties there would be considerable activity in the extension of this class of working.

So far no movement with regard to electrification has taken place in Scotland, and if reference is made to the map of England it will be noticed that at every point where electrification has been adopted there is density of population and a consequent density of passenger traffic.

With the exception of Glasgow and the Clyde Valley area there is nothing like the same density of passenger traffic in any part of Scotland as obtains in England, and in the evidence given before the National Wages Board in connection with the case for a reduction in railwaymen's wages it was stated that for every mile of railway in England 77 777 pasengers were carried, as against 33 675 for every mile of railway in Scotland, but these figures only in a measure account for the slow movement in the direction of electrification on the part of Scottish railway management.

There was the difficulty of obtaining reliable figures as to the value of the results following electrification, the absence of uniformity of equipment necessary for the interchanging of locomotives and rolling stock, and the undeveloped condition of the electric power industry.

The situation to-day is entirely different and the high cost of railway working has made it necessary to seek for every means of economy. If it is ultimately found that the electrification of suitable railway sections offers advantages over the present system of operating, taking into consideration the increased capital expenditure, electrification will no doubt be adopted.

The Electrification of Railways Advisory Committee have submitted their final report in regard to regulations, so that future electrification in this country may be carried out to the best advantage in regard to the interchange of electric locomotives and rolling stock, uniformity of equipment and/or other matters, and, while the Committee recommend certain conditions, they do not put any difficulties in the way of the adoption in future, with the approval of the Ministry of Transport, of any improvement in methods or appliances which may from time to time become available with increasing knowledge and experience.

The Railways Act of 1921 is another factor in the direction of uniformity, and while there may be differences in detail of equipment between groups, it is obvious that within groups there will be absolute uniformity in order to obtain the greatest economy and interchange of locomotives, rolling stock and other apparatus.

While the recommendations of the Advisory Committee may seem easy of fulfilment, it must be pointed out that many costly alterations will require to be made to the existing running line before electrification can become generally adopted, especially in regard to overhead equipment.

It will also be found that many bridges and tunnels have not the necessary clearance, and both rail-level and overhead equipment will have to be provided.

The problem now facing railway management is not merely based on the average number of passengers or tons per train-mile; it is more in the direction of finding a cheaper and quicker means of transportation over the existing lines, giving less congestion at terminals and yet providing for the future growth of traffic.

In general, railway receipts are proportional to ton-miles, and operating expenses to train-miles, and while every effort has been made to increase train loads it has not been possible to dispense with the frequent train service demanded by traders and passengers, and at a time like the present, when loads are at a minimum, practically the same number of trains has to be run as if loads were at a maximum—with the consequent difficulty of making the ton-miles receipts meet the train-miles expenses.

Motor vehicles, run over main public roads maintained at the taxpayer's expense (and the railway companies are perhaps the largest taxpayers in the country), are to-day competing with rail transportation for passenger and goods traffic, and, while it would seem that railway transportation should be cheaper, it is undoubtedly the delays inseparable to slow-moving, heavy traffic that have materially contributed to establishing the motor vehicle industry, which offers, as its one chief asset, quick delivery to the point where the goods are required.

If the present system of traffic working, especially short-haul traffic, does not efficiently serve the more congested districts through which the railways pass, something should be done to make certain that the traffic is not diverted to motor vehicles, as it is by no means certain that the revenue raised from long-distance traffic alone would pay for the upkeep of the railways.

It has to be admitted that the experience already gained in this country goes to show that, generally speaking, the existing electrified lines have justified their existence by paying their way and creating new traffic.

So far the principal field for electrification has been short-haul passenger service, and the greatest advantage is quicker acceleration and deceleration. In the case of short-haul suburban traffic, electrification has not only brought about an improved all-day business but has relieved the congestion at termini.

Multiple-unit trains have proved themselves to have enormous advantages over steam trains for this class of service, inasmuch as the system gives greater flexibility, and train loads can be varied according to the amount of traffic. The space of platform occupied is very much reduced, and short trains at frequent intervals can be run, as against long trains at less frequent intervals. Multiple-unit trains for suburban traffic also lead to many economies when compared with the corresponding steam trains, inasmuch as there is more mileage per day from guards and motormen, giving greater efficiency and less cost per train-mile. Power is used only when actually wanted, and there is an entire absence of smoke and cinders. In addition, there is less shunting and a consequent saving in staff, and, as reduced shunting means fewer movements of points and crossings, the life of these expensive items is lengthened and maintenance cheapened.

Station premises have been re-designed and put to a more valuable use, and the adjoining property has increased in value ; also, it is recognized that residential districts improve in popularity when given a service of electric trains.

During the past few years great progress has been made in the design of electric locomotives, and the substitution of electric for steam locomotives, notably on the North-Eastern Railway, is an indication that the advantages and economies are known and appreciated.

The fundamental difference between an electric locomotive and a steam locomotive lies in the fact that while the latter generates its own power the former only acts as a transformer of the power generated at a power station into haulage power on the track.

Sir Vincent Raven, K.B.E., the Chief Mechanical Engineer of the North-Eastern Railway, in a recent paper * gave the mechanical disadvantages of the steam locomotive as follows :—

" The locomotive being a complete independent unit, its power cannot be greater than the capacity of the boiler.

" To increase the boiler capacity obviously implies increased dimensions and weight, both of which offer great difficulties in regard to clearances and strengthening of bridge structures.

" On many British railways the limit of weight has been reached and further development of power is only possible at enormous expense.

" The boiler, cylinders, valve gear, crank-shafts and all reciprocating parts are costly to maintain. Turntables, fuelling plant and water-supply appliances must be provided.

" The cab is small and open to the weather, involving discomfort to the locomotive crew.

" The locomotive radiates heat and uses coal all the time steam is up, that is, during many hours when it is doing no work and either standing-by or coasting.

" The wear and tear of the locomotive on the track is considerably increased by the impossibility of accurately balancing the reciprocating parts."

Sir Vincent Raven said that the electric locomotive is not hampered by any of the above-mentioned objections and that it possesses other important qualifications, such as :—

- The simplicity of mechanical construction and operation.
- The increased power of acceleration.
- A high scheduled speed, due to the possibility of heavy, short-period overloads, resulting in more frequent service and the increased use of existing tracks.
- A uniform turning effort, resulting in a better factor of adhesion at starting and on gradients.
- The absence of all reciprocating movement, and accurate balancing of all rotating parts.
- Facilities for driving from both ends of a locomotive.
- The accessibility of mechanical and electrical parts.
- Better accommodation for locomotive crews, by reason of the increased available cab area and by the closing-in and heating of the cab.
- The possibility of coupling two or more locomotives together under the control of a single driver.

It is evident that the working of a steam engine depends to a large extent on the skill of the crew in attending to the fire and the water-level, and in looking after a number of mechanical parts and generally " nursing " the engine so as to get the best out of it.

The process of preparing a steam engine for a day's work involves considerable time and labour, and after the day's work is finished there is another process of cleaning up and inspecting which also takes much time and labour.

The electric locomotive is always available for service, as it is only necessary to keep the motor clean, lubricated and provided with brushes in order that it may be always ready for immediate use by simply connecting it to the power line. The driver has only to step on board, close certain switches and move the controller handle, and when the day's work is over nothing has to be done except ordinary examination, oiling and cleaning for the next trip.

The electric locomotive can remain in continuous service if the traffic can be so arranged for at least 20 hours in every 24, that the lubrication and the small amount of cleaning necessary for the electrical equipment can be given by the crew at wayside stops during running and between trips. The driver will, of course, be fully occupied during running in watching signals and controlling the speed, but as the second man is not required directly in operating he will have plenty of opportunity to attend to the cleaning and inspection of all parts, where this can be done without interfering with the running and without risk to himself.

The shed work is reduced to the cleaning and inspection of brake blocks and the less accessible parts between the frame. These differences in preparation for service

* *Transactions of the North-East Coast Institution of Engineers and Shipbuilders*, 1921–22, vol. 38, p. 173.

and operation make it evident that the electric locomotive can remain longer in actual service and do more train-miles than the steam locomotive.

These are only a few of the advantages of electric locomotives over steam locomotives and, while they may seem to be all-important, it remains a fact that there are only very few of them working in this country.

The handicap of electric traction is that it must be instituted on a large scale. It is not possible to change one train only as in the case of a shipping company, which might put one vessel of a new type into commission at a time without interfering in any way with any other ship. To form a fair guide, any experiment has to be tried on a scale which involves heavy capital expenditure, which in these days is difficult to arrange for satisfactorily, while the risk of a comparative failure has to be carefully avoided. The term "failure" does not imply mechanical or electrical breakdown or even financial ruin, but it is obvious that if to the present capital an additional capital equal to the cost of electrification has to be added, the improvement in operation must be equal to furnish a return covering the whole.

The smallest experiment in the direction of electrification would involve a tremendous addition to the capital expenditure, with the consequent difficulties of earning the additional interest charges thereby involved.

It has been pointed out that all the first costs of electrification need not necessarily be charged to capital, e.g. the cost of electric locomotives or rolling stock can properly be charged to revenue under the ordinary process of renewals, as obsolete steam plant requires replacement and in many areas it would not be necessary to incur the cost of power stations, as under the Electricity (Supply) Act, 1919, energy can be purchased in bulk from the public supply companies at probably a lower cost than energy could be generated by the railway company.

Electricity would, of course, only be purchased in cases where the supply was adequate in quantity and regularity to meet the demand, and there is every reason to expect that the concentration of supply for railways and other purposes will bring about lower rates.

It has been said that the greater utilization of the available water power in Scotland would bring cheap energy to the assistance of the Scottish railways, but it has to be remembered that there is a limit to the length of the transmission line, i.e. a point at which the advantage of the hydro-electric power station is wiped out, and it is very doubtful whether hydro-electric power stations will ever be able to compete with turbo-generating stations in industrial areas.

It cannot be said that the Advisory Committee in standardizing a pressure of 1 500 volts d.c. added to the cost of electrification, and up to the present no other system has been put forward giving more economical results in working or showing less capital expenditure for equipment and rolling stock. The importance of having a standard system will undoubtedly lead to more definite progress and, as a result, cheaper equipment. As the result of standardization the manufacturing companies have made great preparations to cope with the railway demand. They are at the present time spending considerable sums on research work and so far they can claim to have carried out all the electrification of British railways.

During the past year many papers were read before this Institution descriptive of new or improved methods of dealing with the problem, and it is known to those interested in the subject that progress is being made along lines which will eventually reduce the cost of installation.

The practice of British railways has been to build and maintain, with considerable credit, their own steam locomotives and rolling stock, and whether this practice of building will be continued under electrification is a question for the future.

Shops for maintenance, repair and renewal will always be necessary, and the valuable experience gained in this direction would seem to indicate that there will be little if any change in the practice. It will, of course, be necessary to purchase electrical equipment for some time, but there is no reason why the mechanical part should not be built by the railway company, who know exactly what is required for their particular line.

Sir Vincent Raven, in his paper already referred to, deals with this aspect of the subject and he has built the mechanical parts of all the electric locomotives in use on the North-Eastern Railway, the electrical equipment being purchased from manufacturers of electrical plant.

Mr. Roger T. Smith, Chief Electrical Engineer of the Great Western Railway, read a paper before the Institute of Transport on May 8, 1922, in which he said that it seems worth while on the eve of a demand for electric locomotives for the railway companies to consider whether an organization and workshops design for efficient and successful maintenance is the best for constructing electric locomotives requiring electrical and mechanical research of the highest order, and the employment of every advance in electrical and engineering knowledge, not only in locomotive building but in several branches of electrical engineering. He went on to say that it also seems worth while to consider whether it would not pay the railways of this country at least to give a fair trial to the policy of helping to build up the manufacture of the electric locomotive by commercial firms who, with an important home market as well as a foreign market, would have an opportunity of creating a world trade.

Very little has been said in regard to the cost of electrical equipment for ordinary railway lines used for both goods and passenger traffic, and in his paper already referred to Mr. Roger T. Smith gives the cost per single mile of track at £4 000, i.e. £2 000 for line equipment and £2 000 for substations spaced 10 miles apart. This sum does not include anything for transmission, which might, in the case of some districts of Scotland, cost a great deal.

It cannot be said that all the pioneer work has been done; but what has been done has proved to be wonderfully successful. The element of uncertainty has been entirely eliminated and I am of opinion that electrification will go forward as rapidly as economic conditions justify the expenditure.

SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By H. WEST, Associate Member.

(*Address delivered at* SHEFFIELD, *15th November*, 1922.)

I have decided to take for my address a subject with which I have been closely associated for the past 26 years, that is, "The Use of Electricity in the Iron and Steel and Allied Industries." In reviewing this subject it is not my intention to go very closely into details, but to confine myself to a general outline only, of what has been accomplished, followed by a brief statement regarding the important question of supply, and, finally, comments on some defects associated with present-day apparatus.

It is generally admitted that the iron and steel industries have for ages occupied a position of vast importance in the world, nor can the statement be gainsaid that the economical production of these metals is a matter of national importance. Iron and steel have played a greater part in the upbuilding of the material side of our civilization than any other metals. They represent an enormous investment of capital and are produced upon a scale not attained by any other industry, and it is undoubtedly true to state that the enormous progress which has been made in the development of the industry during recent years is in a great measure due to the economies effected by improved facilities for driving plant, handling materials, and conducting certain electro-thermal and electro-chemical processes which naturally followed the introduction of electricity.

The services rendered during the recent war established beyond doubt the great superiority of electricity as a means of transmission and utilization of power over all other methods; in fact it is now universally conceded that it stands first and that there is no good second.

Those who have visited a modern iron and steel works of large size will agree that there is no industry in which there exists a greater variety or number of difficult problems to be solved than in the application of electricity to the requirements of such works, and that this application has made gigantic strides during the short period which has elapsed since its introduction.

It is probably true to say that more electrical power per head of working force is used in the steel industry than in any other industry; in fact it has become so much a part of the everyday life of the plant that few realize how dependent we are upon it. From the office to the despatch bay in the works it plays an important part, whether it be used for addressing envelopes, ringing bells, or driving the heaviest machinery; in fact, directly or indirectly, every operation is dependent upon its aid.

Some idea may be formed as to the magnitude of the equipment required to meet the needs of a concern engaged in the production of iron and steel and the associated businesses of shipbuilding and railway rolling-stock manufacture, when it is considered that for this purpose a total of something like 2 800 motors are required, having an aggregate brake horse-power of about 90 000, and ranging in size from a fraction of 1 h.p. to a little under 20 000 h.p., with generating and/or substation plant sufficient in capacity to meet the demands created by these motors, together with that due to other uses of electricity.

During the later years of the war a number of the best-known concerns in this district were collectively using something like 220 000 000 units of electricity per annum. The requirements of this same group were met immediately before the war by something under 80 000 000 units in the same period. Nevertheless, a little over 30 years ago an electric motor was a rarity in a steel plant in this country, although some progress had been made abroad in this direction. Prior to that time, electrical engineers at home had devoted so much attention to the then important questions of central electric light and traction stations that they had little time to consider the industrial use of electricity which was destined to play such an important part in the years which followed. True, a few far-sighted men were using this drive for certain specific purposes, but these applications formed conspicuous exceptions. In general, those connected with the industry were sceptical regarding the suitability of an electric motor to meet the exacting demands of steel-works practice. The drives then in use were at least satisfactory and represented what engineers had found to be the best after many years of experience. If the plant was making money, what need to change? If not, the cost of installing motors was prohibitive.

Some of these early applications related to machines which required to be diffused rather than concentrated, e.g. punching, shearing, and bending and straightening machines, cold saws, etc. It had been the general practice to place a separate non-condensing engine to operate each of such machines and distribute the power thereto by an extensive system of steam pipes from centrally placed boilers, or from a multiplication of boilers distributed in small groups, each group requiring separate labour for firing and for coal- and ash-handling. Not only was the production and delivery of the steam to the various points wasteful, but there was also a tremendous loss in its use, as a consequence of the continuous running of most of the engines, although they were doing useful work for only a small portion of the time.

The advent of electricity rendered possible a great advance, as a more economical type of engine centrally placed could be employed to drive a dynamo, with

cables instead of steam pipes, and motors directly applied to the machines.

Following the class of machinery already mentioned, steps were taken to drive machine tools, live rollers, screw-down and skid gears, and cranes of various types. In every instance the displacement of uneconomical engines and long lengths of steam pipes or shafting led to further economies in the cost of labour, fuel and upkeep, and a much more flexible and efficient form of drive was secured, with the advantage that the driven machines could be more conveniently placed in relation to each other and the work in hand.

In the face of many failures of these early machines, the motor attained a responsible position, and the new system became so unanimously recognized as being sound that the progress of conversion of existing plants and the application of motors to new drives where possible went forward with great speed, until to-day the electric drive is the only one considered for all purposes to which it can be applied.

With the ever-widening duties of the motor came attempts to apply it to the heavy main drives of the rolling mills themselves, and in entering this field, so long held exclusively by the steam engine, it met with the greatest opposition on reversing mills, the major causes of which were probably prejudice and initial cost. The progress made in this direction, however, can also be recorded as remarkable. During late years it is represented by a very steeply rising curve, and there now remains very little argument in favour of the steam engine for such drives. In connection with this curve, it may be of interest to mention that the first electrically-driven mill was set to work in Sweden about the year 1890, and the first large equipment in this country was installed in 1904.

To-day, according to a recent table,* there are now over 600 electrically-driven mills in operation, the driving equipment for which was supplied by British manufacturers, and the great bulk of which are installed in steel works in this country. The list constitutes a marvellous record of development, and comprises mills capable of turning out all classes and forms of rolled materials, inclusive of tubes, tyres, sheets, rails, girders, etc. Considerable impetus to the advancement of this class of drive was created by the development of adequate and reliable gearing. This rendered the low-speed motor, to a large extent, unnecessary, thereby reducing the cost of many installations.

There are naturally a number of varieties and types of these applications, depending upon the drive in question. If the drive is a continuous one, i.e. if the mill is so arranged that the motor runs continuously in one direction at a constant speed, the application is comparatively simple, as the wound rotor, three-phase induction motor serves the purpose admirably.

If the drive in question is one demanding reversal, with or without speed regulation in either direction, the application of the motor becomes more complicated, due mainly to the size of machine required, coupled with the rapid reversals necessary. In this case one has recourse to the Ilgner system which has previously met with great success in its application to large mine hoists.

* *Electrician*, 1921, vol. 87, p. 647.

Other methods have been developed for meeting special requirements, but I do not propose to dwell further upon this subject.

There still remain a very large number of engine-driven mills, and it would seem that the greatest field for additional motor-drives in the next few years lies in replacing many of these engines, as doubtless such a step would lead in many cases to economy and increased output.

One of the fundamental considerations controlling the rapidity of production of steel is the handling of materials at all stages during the process of manufacture, and in this connection overhead and other numerous special types of cranes have contributed in a very large degree to the present-day highly developed state of the plant, but again such progress was only rendered possible by the adaptability and ease of control of the electric motor for this purpose. Adherence to the earlier methods employed for the transmission of power to cranes would have rendered unattainable the varied movements and operation which are to-day possible.

One great extension in the use of cranes is due to the increasing employment of electromagnets for rapidly and cheaply handling materials at various stages between the stock yards and the shipping department. Very great economies in this item of labour alone have been effected by such means.

Apart from applications involving power supply for mechanical operations, electricity has, of course, been employed for a great number of years as the principal lighting agent, and it has found new fields for itself in connection with the reduction of ore, the melting and refining of steel, the electro-deposition of pure iron, and the electrostatic precipitation of suspended particles in blast-furnace gases intended for use in gas engines. It has also been successfully employed as a means of producing high temperatures for re-heating purposes, and again, through the medium of the pyrometer, for indicating and recording temperatures in connection with all parts of the plant.

As a means of jointing metals, in repairing cracks or breaks, salvaging defective castings, and for metal-cutting purposes, all included under the general heading of "Electric Welding," electricity has proved of great service. Prior to the war, little had been done in this respect, but great strides were made when the confidence of the engineering world was established due to the successful welding carried out on the damaged parts of the interned German ships at New York in the spring of 1917.

In a lesser degree it has been of service to the metallurgical chemist, who has applied the electrolytic method to the separation and determination of several of the metallic constituents of steel. Up to the present—setting aside the question of lighting—the production of electric steel is the most important of these special applications.

The use of the electric furnace was somewhat limited before 1914. It was, however, making headway, although then regarded as being in its experimental stage. After the outbreak of war, the demand for a greatly

increased output of special alloy steels, coupled with the necessity for providing a means of dealing with the enormous accumulations of turnings produced in the manufacture of munitions of war, resulted in the number of furnaces being rapidly increased, until at the cessation of hostilities there were upwards of 140 in service or in course of erection. About 120 of these were for purposes of steel manufacture and had a total charging and kVA capacity of 384 tons and 98 769 kVA, respectively, and a total nominal output of about 31 000 tons per month, based upon five days per week and four weeks per month. These figures are quoted from a paper by Mr. R. G. Mercer,* to which I would refer members for very valuable information on this subject.

Unfortunately, I cannot enlarge here upon the processes of electro-deposition of pure iron or electro-smelting of iron ore. I shall, therefore, confine myself to the statement that both processes have been successfully employed on a commercial scale and offer great possibilities for the future, given an abundant and cheap supply of power.

A question which has recently caused a great deal of controversy in steel works circles is that relating to the respective merits of alternating-current and direct-current plant for the purposes of any particular service. Each system possesses peculiar merits of its own, and as the iron and steel works of to-day either generate or receive at least a portion of their energy from public supply mains on a high-tension multiphase system, there is an increasing tendency to utilize, wherever possible, a.c. apparatus in place of the d.c. type which so long held the field, owing to the saving which can be effected in copper, transformers and converting plant.

With regard to motors, the principal factor deciding the type is that of speed control, but it may be generally stated that machines of either class will give equal satisfaction on certain drives if at the time of selection all phases of the problem receive full and proper consideration. This statement is based upon my experience in connection with an a.c. plant laid down 16 years ago for all purposes in one of the works over which I have control. The drives included cranes and mill auxiliaries, comprising "screwdowns," skids and live rollers, and, though much trouble was experienced due to certain motor defects to which I shall refer later, I am confident that the duties were as satisfactorily performed by this class of machine as would have been the case had any of the available d.c. machines been used in their place.

No matter in what branch of electrical work a man may be engaged, he is always interested in electric power generation. From the foregoing general outline of what one may term the consuming devices in his charge, it will be readily conceded that the problem of supply, whether it be derived from outside sources, or generated within the works, is of profound importance and interest to the steel works electrical engineer.

The question of supply is to-day a much more vital one than when lighting constituted the main bulk of the load, and the three main considerations, all of equal importance, are continuity of service, safety of plant and workers, and low cost per unit.

* *Journal I.E.E.*, 1919, supplement to vol. 57, p. 254.

Considering the capital involved and the nature of the work in hand, an interruption of the supply, even for a few moments, is a very serious matter, and every precaution should be taken to avoid it, as not only does it lead to loss of output, but the lives of many of the employees are placed in jeopardy, partly due to the extinguishing of the lights, should the failure occur during the night, but mainly due to their position in relation to molten or hot metal. In many cases great monetary loss is occasioned by the cessation of supply during casting operations, rolling, forging or otherwise dealing with molten or hot metal. Damage also frequently occurs to electrical and other machinery due to the inability to remove it from hot places or out of contact with heated materials. Danger also arises due to the impossibility of operating pumps for the purpose of the works water supply or the important duty of boiler feeding.

For many years all the electric power was produced within the works by privately owned plants which, from very small beginnings, had been extended from time to time to keep in step with the ever-increasing demands made upon them, until, in many cases, such plants were of relatively large capacity compared with the then existing central generating stations. There was then no question as to the advisability of generating their own power, as this was the only way in which it could be obtained.

These earlier installations were, in the main, of the d.c. type, the supply pressure being usually 220 volts, determined by the initial class of motor available, and partly also by considerations of safety. The handicap of this low voltage was keenly felt, as the load and areas to be covered increased, due to the continued extensions of the plant. This difficulty was overcome in some instances by the simple plan of modifying the arrangement to that of the three-wire system, balancing all existing motors and lights on either side of the neutral and connecting any additional motors across the outers. In other instances, plant laid down for extension was of the a.c. type, giving a supply at medium or high pressure which could be applied direct to many motors without the intervention of either transforming or converting apparatus.

Since many of these stations had been kept up to date by replacing obsolete equipment as more efficient and larger units became available, and especially in those cases where waste heat was utilized for generating purposes, the cost of electricity was exceedingly low. Moreover, as the questions of simplicity and reliability were constantly uppermost in the minds of those responsible for the lay-out and operation, it naturally followed that the three important requirements already quoted were usually met in a most satisfactory manner.

The feeling of security associated with this state of affairs was, for a time, a deterrent to the adoption of a supply for part or the whole of the requirements, derived from a company-owned or municipally-owned station. Later, however, this class of service was accepted in many instances in preference to extending or renewing the private plant, especially where waste heat was not available in sufficient quantity, or in

congested areas when the question of space, or of water for condensing purposes, presented difficulties.

It is seldom that a failure of supply can be attributed to a total shut-down of station plant. More often than not it is due simply to the opening of a feeder switch. When this occurs in the case of the privately owned plant situated within the works, it is a matter of only a few moments to restore the supply. In the worst case, assuming that the whole of the generating units are disconnected from the busbars, the engines will continue to run with the machines excited, thus enabling one of their number to be immediately put into service to supply those departments where risks of loss of molten or hot metal are existent.

The matter is not so simple in the case of a large consumer dependent upon an outside supply, as due to the nature and pressure of the supply considerable extra apparatus is required to deal with it before it can be passed on to the works, and, unlike the illustration given for a private station, much additional, valuable time is lost for the purpose of starting and synchronizing converting machinery and operating the extra switchgear involved.

Interruptions of longer duration due to causes of a more complex nature almost invariably lead to a greater loss in the case of an outside supply than with private plant, as in such instances one is usually ignorant as to when work may be resumed. This leads to great uncertainty concerning the best course to adopt in order to reduce the consequential loss and danger to a minimum.

Although the cost of electricity does not represent a very large proportion of the total cost of each ton of metal produced, with the exception, perhaps, of that used for melting purposes, it is nevertheless of the utmost importance, considering the enormous amount of the annual bill, that every endeavour should be made to reduce it well below the prices ruling at present. In view of this, and also the necessity for conserving the nation's fuel supplies, it would seem to be incumbent upon those concerned with the reorganization of the electricity supply of the country seriously to consider close co-operation with steel and other works with a view to the utilization of all available waste heat, as undoubtedly this would lighten the burden arising out of the high cost of fuel and its conveyance to the point of use.

Any further segregation of the power plant from the steel works will depend largely upon the success of efforts in this direction, and also upon the requirement that uninterrupted service throughout the year can be guaranteed by the provision of adequate devices for the purpose of isolating faulty apparatus, or sections, without interference with the sound ones.

Another serious handicap to the immediate displacement of all private plant and, to some extent, the continued safe operation of apparatus already connected for the control of outside supply, arises out of the present-day trend towards increased capacity and the connecting together of public generating stations. This centralization of large amounts of energy introduces serious possibilities of considerable destruction should a short-circuit occur on a consumer's premises, and places very great responsibility upon the reliable operation of high-voltage apparatus, in particular upon extra-high-tension switchgear. The capital expenditure required to guard against such possibilities will be greater than that entailed when connecting up to a less pretentious scheme, thus tending to discount any advantage to be gained by the utilization of large and more efficient units. This fact alone renders necessary a reduction in the unit charge for extra-high-tension energy to enable the outside supply to compete favourably with the private plant from the point of view of cost per unit at the low-tension works switchboard.

I have already stated that steel-works present a number of difficult problems in the application of electrical apparatus. These difficulties do not disappear with the installation and setting to work of the machines, etc., but rather give way to a number of others arising out of the unsuitability for this special purpose of much of the available equipment.

Generally speaking, the steel-works plant itself is massive, rough, and subject to severe shocks and stresses. Its limits of adjustment are wide, and it is in the care of men who are accustomed to materials, tools and methods which are the reverse of delicate. It is, therefore, necessary that the electrical equipment should be selected with care, the purpose in mind being reliability, simplicity, the human element, interchangeability and easy renewal and repair. Above all, it should be rugged in build and not liable to deterioration due to the ever-present corrosive gases and dirt-laden, hot, and often humid atmosphere.

Since the processes are continuous ones, and the stoppage of one machine frequently holds up a whole section of the plant, it is just as important to guard against breakdown as it is to ensure continuity of supply to the machines. The first equipments included apparatus of the then standard designs, but it was soon evident that something entirely different was required for this special service. The early motor at least, with all its faults, was a more reliable article than the starter of those days, and much excitement was at times occasioned when starting up some of the motors, due to the nature of the only available starters, which consisted of coils of iron wire arranged to be cut out in steps by means of a multiple-contact switch, but without any device to protect the contacts from the destructive sparking which occurred. A separate switch—not interlocked with the starting handle as is usual to-day—was provided in the shunt field circuit. The latter was, of course, intended to be closed before, and opened after, manipulating the starter handle. On occasions this sequence was followed, and when the unsupported resistance coils or the arm and contacts of the starter did not form too close attachment for each other the motor in due course acquired full normal speed. There were times, however, when the operation was incorrectly performed, and both the operator and the motor exceeded the speed limit, often with disastrous results to the latter.

As most of you are familiar with the great improvements which are embodied in the starting and controlling apparatus available to-day, numerous types of which have been developed to overcome the difficulties which

bitter experience has pointed out, and to meet the demands of modern practice—assisted in great measure by the requirements of the Home Office Regulations—it is not my intention to refer to the various stages through which progress in this connection has carried us, but I should like to point out that, notwithstanding the many excellent examples, there still remains room for considerable improvement with a view to the reduction of the cost of upkeep and the removal of the uncertainty in regard to correct operation. For instance, resistances in many cases are deplorable. They are neither durable nor dependable, due to their liability to corrosion and breakage. The method of assembling, clamping and ventilation often leads to endless trouble. Then, again, the switch parts and contact surfaces are frequently incorrectly proportioned, thus causing heating. Interlocks, forming a very vital part of many modern equipments, are much too flimsy in character.

Much of the switchgear of other classes required for use in steel works also leads one to hope for improvements. Overcrowding of details, and unnecessarily light construction, often lead to trouble, while many otherwise excellent designs are frequently marred by the inclusion of terminals or trifurcating boxes totally unsuited to the size of cable required for the job in hand. Back or internal connections are also a constant cause of failure, in consequence of the slipshod manner in which they are arranged.

Unfortunately, the trials of the engineer do not end with switchgear. Motors also cause him much anxiety, due to their deficiency in mechanical strength. The frequency of reversal, and the heavy jars to which the motors are subjected, often lead to fractured end-brackets or to the armature or rotor core rotating round the shaft. The use of insulating materials unable to withstand the rough usage or action of corrosive gases leads to frequent failure, and many instances exist of otherwise good machines being spoiled by the inclusion of shoddy terminals or brush-holders.

Again, we have all at some time or other suffered inconvenience and expense because of the difference in speed, rating and dimensions of the various makes of machines. It is not always possible to carry sufficient spares of each type to meet all demands, and, although the differences mentioned are often apparently small, there are, nevertheless, definite limitations to the substitution of one make of motor for another. In the early days, and even at the present time, the manufacturers have standardized this lack of interchangeability. An initial order for motors seemed to be considered a virtual guarantee of subsequent orders, due to the well-recognized reluctance to carry a greater range of spares than necessary; yet the modifications introduced by the makers themselves in the normal improvement of design have rendered many of the earlier features obsolete, and have thus, in effect, increased the number and range of spares required even where a given make of motor may have been retained throughout the works.

The steel industry, constituting, as it does, one of the most remunerative fields for the activities of the electrical equipment manufacturer, it would seem to be well worth while to spare no efforts to develop a line of apparatus and machines in every respect adapted to meet the exacting requirements outlined. Something has been done in this direction so far as the "live roll" motor is concerned, but surely it should be possible, through the medium of their organization, definitely to fix the principal mechanical dimensions of these and other machines, such as the length and diameter of shaft, the size of bearings, the distance from the centre line of the shaft to the underside of the base, the spacing and size of foundation bolts, as well as horse-power rating, speed, and type of brush.

With limitations only of these characteristics, each manufacturer would still be at liberty to improve, if possible, details of both mechanical and electrical design, and thus maintain wholesome competition and progress.

Before bringing my remarks to a close, I should like to thank the authors of several previous addresses and articles which have appeared in the technical Press upon which I have drawn, to some extent, for the purpose of finding, in some instances, a better way of expressing what I so strongly think and feel.

In conclusion, I would remind you that the iron and steel industry is passing through the most trying time that has ever been known or heard of, and that when we do again get the whole of the wheels turning it will be incumbent upon each one of us concerned to exercise the utmost economy in the arrangement and running of our plant, so that by its greater efficiency it may assist in no small degree in meeting the competition which is certain to be encountered.

With due regard for established precedent, we should be ever alert to grasp the significance of new ideas and, with the courage of our convictions, to adopt them, but

> Be not the first to cast the old aside,
> Nor yet the last by whom the new is tried.

Such advice is indeed conservative, and by following it we can make the electrical departments of our steel works of enormous service and value, not only to the great industry itself, but also to the nation in general.

TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By W. P. Richmond, Associate Member.

(Abstract *of address delivered at* Middlesbrough, *16th November*, 1922.)

At the beginning of the last session the trade of this district was in a very bad state, and we hoped that by now conditions would have become more normal, but there is no doubt that Cleveland is passing through the darkest days in its history, with perhaps the one exception of the crisis in 1879. The present crisis differs from all its predecessors, however, in that it is universal. Our trade conditions, bad indeed as they are, prevail throughout the United Kingdom and extend to every corner of the globe.

To understand properly the present crisis, we must first of all investigate the general causes underlying the world-wide depression, applying the results of that examination to our own patricular case, and then take into consideration any local or immediate difficulty.

We shall see that the causes are of two orders: (1) General and international; (2) National and local. Although these two are inextricably related, I propose, for purposes of clarity, to deal with the two separately.

General and International Causes of Trade Depression.

For any industrial country to be prosperous it must have foreign trade, and the non-existence to-day of international trade is the cause of the present world-stagnation. The causes of the non-existence of international trade are threefold :

(*a*) Reparations, and allied and other debts.
(*b*) Fluctuations in foreign exchanges.
(*c*) Bad policy in the new commercial treaties and regulations.

(*a*) *Reparations, and allied and other debts.*—Following well-known economic laws, the payment of war debts naturally forces up taxation on the one hand, and on the other produces an adverse effect on national credit abroad. The allied nations must be in unison, and it is obvious that the only remedy is one which will set Central Europe upon her legs again, first so as to be able to pay any reasonable demand made upon her, and secondly so that she can again become a fruitful market for our produce. With this should be coupled some desirable method for the liquidation of war debts.

(*b*) *Instability of foreign exchanges.*—Immediately after the war the German exchange began to fluctuate enormously, largely, as we have seen, as the direct result of war debts.

At the same time, the exchanges in other countries began to fall, for similar reasons, only perhaps not to such a colossal extent, and gradually all foreign markets became closed both to ourselves and to America, because our prices were prohibitive, and eventually the exchange question developed to such a degree that foreign iron and steel could be sold in the Tees-side district at shillings below our cost of production and still give a good profit to the foreign manufacturer.

This state of affairs must be remedied before international trade can be re-established to its pre-war degree, with certainty, profit and mutual advantage. The remedy lies in reverting to a gold standard in all countries, as well as in keeping annual national expenditure within the limits of annual national revenue, this latter, of course, applying particularly to Central Europe. This means, above all, considerable reduction in the amount spent on armaments. At the International Financial Conference at Brussels in 1920 it was shown that on an average over 20 per cent of national revenues were spent on armaments ; also that, as far as Great Britain is concerned, 60 per cent, or 12s. in the pound, of the taxes is spent on wars, either old or new.

(*c*) *Bad commercial policy.*—Several countries have introduced since the Armistice various trade regulations whereby the importation of certain articles is prohibited. The object of these regulations seems to be to make exports exceed imports. Now, it is wrong to imagine that because a country exports more than it imports it must be flourishing, since the exact opposite might easily be the case. Actually the ratio of exports to imports has no direct bearing upon the flourishing condition or otherwise of a country. This scheme must not, however, be confused with legitimate tariff reform, which has as its object the raising of national revenue. The obvious remedy in this case is the abolition of such regulations, with a view to fostering—not hindering—trade. Time, however, will do much to teach misguided countries that such methods are wrong, and will only defeat their own objects.

Such, then, are the general causes of the present world-wide depression, and it would be well now to investigate the immediate causes in the light of the foregoing, remembering always that Cleveland and its trade form but the part of a whole.

National and Local Causes of Trade Depression.

Iron, steel and shipbuilding are our local staple industries, and on the cessation of hostilities in 1918 the whole world was crying out for iron and steel. Various industries had been starved during the long years of war. Railroads badly needed repairing ; in some cases even replacing, and rolling stock, etc., was depleted. Yet, as we have seen, the boom was but short-lived. Whilst the demand was good, the supply fell far short of expectations. There was a shortage of coal supplies, and also of ironstone. To

this difficulty was added another, namely, the truck shortage, causing delays in securing supplies and despatch of finished products. Then came the moulders' strike, the engineers' strike, the coal strike and the railway strike. The combined effect of these was to cause many furnaces to damp down, whilst others on reduced blast were only able to produce poor quality pig instead of good marketable brands. Much valuable coke was thus uselessly consumed. Then, because our supply in no way met the demand, iron-masters refused to allow the export of pig iron until the home markets were satisfied. The removal of the embargo was subsequently brought about, but unfortunately not until foreign markets were closed to us.

Such was the position in 1919, but by the end of 1920 the reverse was the case, for what little demand existed was met by cheap foreign iron and steel.

The Future of the Cleveland Industries.

On the eve of war the world consumed 80 million tons of pig-iron and steel ingots per annum. As a consequence of eight years' abnormal conditions there is a world shortage of iron and steel of at least 300 million tons, the major portion of which will have to be replaced within a reasonable period. This is, of course, speaking in the abstract, but there are signs of immediate requirements. Nine countries out of ten are needing vast railway replacements and extensions. Projected schemes in Brazil alone will consume 16 million tons of steel. South Africa has just passed a new Railway Construction Act and has sent out inquiries for material. India requires additional railways of a mileage greater than that for the whole of Great Britain. Bulgaria, Latvia, Belgium and Spain will soon be in the market for railway material.

We have also at the moment 3 million tons of steel ships over the age limit waiting to be broken up and replaced as soon as the price of steel falls sufficiently to enable new ones to be built. Each 2·1 tons of shipping requires 1 ton of steel; thus more than an additional 1½ million tons of steel are required for ships alone.

For some years our pig-iron exports have been falling, but our steel exports are rising, which in itself is a good thing, for it means that more work will be done in the country and in this district. Unfortunately, however, the pig-iron production is not up to the steel requirements in quantity. Steel is fast becoming our staple industry, and we must realize the fact and work accordingly. During the war the productive capacity of our country had been permanently increased. Many new works were laid down; many reconstructed or remodelled and extended, and there is now an ample sufficiency of plant. This also applies to Cleveland and we ought therefore to be in a position to supply steel to a degree hitherto unknown. Moreover, railway rates, while falling, are hardly ever likely to reach the pre-war rate. So, instead of shipping hematite pig to Sheffield to be converted into forgings or boiler plate—as was formerly done—often to be returned to the seaboard for shipbuilding or for export, the tendency will be to lay down additional steel plant in Cleveland. The future of Cleveland therefore appears to be very hopeful.

Electrical Progress.

Turning our attention now to the electrical side of the question, I think we can congratulate ourselves that the North-East Coast is one of the most progressive parts of the country. Our power company is the largest in Great Britain, and ranks as one of the largest in Europe. We have a railway company which has adopted entirely new methods, and has attained extremely good results. We have mines wholely electrically operated, and iron and steel-works almost entirely so. It is the application of electricity to iron and steel-works which mostly concerns us in this district.

One of the first mills to be driven by a motor in this country was a small one at the Queensferry works of Messrs. Willans and Robinson. This was used for cogging-down ingots into blooms from which the tubes for their water-tube boilers were made. The motor was of 285 h.p., direct current and compound wound. When the load came on, the motor slowed down by reason of the compounding and allowed the flywheel to take effect. The power was transmitted to the mill by means of a rope drive. This plant was installed in about 1904.

During the next few years many small drives with no particular points of interest were put in for tin-plate mills and the like. In 1905, however, a very much bolder scheme was adopted at the Birkenhead works of the McKenna Process Company, their works being entirely electrically driven. There were several points of interest in this plant. It was the first time that rolls had been directly driven electrically; the prime movers were the first turbines made by a firm other than Messrs. Parsons, and it was the first large three-phase installation manufactured in England. This plant may be taken as the first serious attempt to electrify rolling mills. A few years later two small reversing mills were installed in this district, followed almost immediately by several "three-high" variable-speed mills. In 1906–7 the first Ilgner sets were put in for the Clyde Navigation Trustees at their new "Rothesay" dock at Clyde Bank, to operate coal hoists and cranes.

These large flywheel sets paved the way for large reversing rolling mills, and in 1911 a large 12 000 h.p. reversing mill was installed in this district, and electrical power had been applied to rolling mills of all sizes.

There is little doubt that the duty of live-roll motors is the most severe that any motor is ever called upon to perform. Particularly so is the case of that immediately before the saw. Motors in such positions are constantly being started, stopped and reversed, so that the power used in starting and reversing is much in excess of that absorbed in doing useful work. For the same reason they have to be put in of much larger size than the actual horse-power required, on account of the excessive heating. What is required is a reversible clutch, and a constantly running motor. Recently there have been several, sometimes termed hydraulic clutches, put on the market. These are not only a clutch but are made with a gear ratio between the primary and secondary motion. If these devices will withstand rolling mill work, and I believe they will, they will be of great advantage for rolling-mill

auxiliary drives. Not only will they supersede controllers or contactors, which require much attention, but they will allow of the use of the ordinary industrial type of motor, as there will be no excessive heating caused by reversing. Still further advantage will be gained and lower first cost attained if the ratio of the clutch can be made so as to eliminate entirely any further reduction gear. Such first costs would be much less than at present, when, besides the special motor now employed, the controller or contactor and the gears—two are usually employed—could be dispensed with.

The Power House.

For several reasons it is somewhat difficult to compare generating costs in works with those of public supplies. The wages in works' power houses usually fluctuate, the men being paid according to the price of iron and steel. The plant has grown with the works, and the plant units are possibly not of a size best calculated to keep down costs. The load factor is in favour of the works, which, of course, generate more cheaply than they can buy. On the whole, however, I think that the cost of generation might be still further reduced.

Both in the lowness of running costs and in the small amount of adjustment and attention required, the steam turbine is far in advance of the gas engine.

Electric Locomotives.

In a few years' time, when the electric locomotive has taken the place of the steam locomotive, we shall look back on the boiler, firebox, cylinder, side rods, etc., of the steam locomotive as a bad dream, for the electric locomotive is bound to come.

The disadvantages of a steam locomotive are that the boiler, cylinder, valve gear, crankshafts and all reciprocating parts are costly to maintain. The cab is small and open to the weather, thus involving discomfort to the locomotive crew. The engine radiates heat and uses coal while steam is up, i.e. during many hours when it is doing no work. The wear and tear of the locomotive on the track is considerably increased by the impossibility of accurately balancing the reciprocating parts.

The electric locomotive is not subject to any of the above-mentioned objections, and, in addition, it possesses many other important advantages.

The North-Eastern Railway have had eight years' experience with the locomotives on the Newport–Shildon line, and Sir Vincent Raven in his paper read before the North-East Coast Institute of Engineers and Shipbuilders in December, 1921, gives the figures for repairs of two steam and one electric locomotive as follows :—

The first steam locomotive after running 51 000 miles cost 5d. per mile.

The second steam locomotive after running 56 000 miles cost 5·572d. per mile.

The electric locomotive after running 100 010 miles cost 1·316d. per mile.

In other words, the cost of repairs for the electric locomotive was only one-quarter of that for the steam locomotive. In the United States the cost of repairs is rather more in favour of the electric locomotive, being only about one-fifth of that for the steam locomotive.

It is not, however, the main-line locomotive which is of the greatest interest to us, but rather the shunting locomotive suitable for use in iron and steel-works. Such locomotives are of two types, the straight electric locomotive, i.e. that getting its supply of electricity from an outside source, and the battery locomotive, and sometimes a combination of both types.

Sir Vincent Raven in his paper read before the Institution of Mechanical Engineers in August of this year instances two straight locomotives which for 17 years have been working on the Quayside line at Newcastle for shunting purposes. They have been in the shops only three times for thorough overhaul, and their daily service occupies about 18 hours. For the whole of the year 1921 the average cost per engine for repairs, inspection, preparing, cleaning, etc., was £103. This figure is rather high, as it includes in one of the locomotives some special repairs which would not be required in an ordinary year. The corresponding figure for steam locomotives doing the same class of work for the year 1921 would be about £610.

The straight electric locomotive is undoubtedly a better engine than the battery locomotive, owing to the fact that the latter must necessarily impose certain restrictions which do not exist in the straight electric locomotive. In making this statement I am not in any way detracting from the usefulness of the battery locomotive, as experience has proved beyond doubt that the battery locomotive is an almost ideal class of engine for industrial shunting-yard duty, and in the majority of cases it is admissible where the trolley electric locomotive could not be considered.

It is impossible to use the straight electric locomotive in the works proper, on account of the necessary overhead line or third rail, but it is advantageous in some cases, e.g. where slag-tips or raw-material stores are at some distance from the works, to use a combination, the battery being the source of supply in the works and an overhead line in the outlying parts.

Probably the first question to be asked is : Will an electric locomotive do all that a steam locomotive will do ? The reply is, of course, in the affirmative. An electric locomotive requires only 80 per cent of the adhesive weight needed by a steam locomotive.

When dealing with the battery locomotive there is a certain limitation due to the heavy rate of discharge which is demanded of the battery when hauling a load up the maximum gradient, but, generally speaking, there is little doubt that most batteries, if carefully designed, are capable of dealing with any ordinary shunting-yard gradient. One may take, say, 3½ to 4 per cent as representing a very severe gradient, and I consider that good results would be obtained on such a gradient if the battery capacity is suitably selected. There are quite a number of battery locomotives running in this country and doing quite satisfactorily all that is required of them, and in the United States at present there are 2 400 in operation.

First cost.—The question of first cost is a very important one and is governed largely by local conditions. If one takes the worst conditions, where only one steam

locomotive is used, and consequently one battery locomotive is to take its place, then the first cost may be a serious handicap, as the capital value will possibly be in the nature of 1·8 for electric battery traction to 1·0 for steam traction, but there are few yards, however small, where one could afford to risk allotting the shunting duty to one steam shunter. However, when one comes to consider the substitution of a batch of steam locomotives by electric locomotives, the capital costs are much more in favour of the latter. From my experience I should say that 8 battery locomotives would carry out the same duties as a fleet of 10 steam shunters.

On the Newport–Shildon line 10 electric locomotives replaced 27 steam locomotives, the former, of course, being a more powerful engine than the latter. In iron and steel-works we are not in such a happy position, as we are not able to make our engines heavier and so reduce the number.

Recently a scheme was investigated for replacing 14 large steam locomotives, each weighing 34 tons, by electric locomotives. It was decided that it would be advisable to purchase 12 electric locomotives at a cost of £115 000. The operating charges of the existing steam locomotives were examined very thoroughly, and only proved results were taken as the operating costs for the electric locomotives, and it was found that an annual saving of not less than £21 000 would result.

Saving of fuel.—Although the saving of fuel due to the use of electric locomotives in place of steam on main lines is very great, it is not nearly so great as that shown in a shunting yard. The saving is again increased in iron and steel-works on account of the locomotives having to stand inactive, waiting for furnaces to tap, and the like, for long periods.

From a great many tests taken on many sizes and types of steam locomotives, it has been found that for every 13 lb. of coal consumed on a steam locomotive 1 kWh is required from the battery of an electric locomotive. Now, allowing for a battery efficiency of 70 per cent, then 1 kWh of battery input is necessary for every 9·1 lb. of coal consumed in the steam locomotive. In a modern power station 1 kWh can be generated by 2 lb. of coal or its equivalent of other fuels, which shows a fuel saving of $4\frac{1}{2}$ to 1 in favour of the electric locomotive. At present-day prices coal such as is used in a power station costs 17s. 6d. per ton, whilst that suitable for a steam locomotive costs 26s. 6d. per ton, showing a 7 to 1 saving in the cost of fuel in favour of electric battery locomotives.

In some cases it may be impracticable to charge the batteries direct from the generating plant, and some means of conversion, such as a motor-generator, may be necessary. The saving of fuel in such cases will not be so great, as the efficiency of the converting plant will have to be accounted for. So as not to favour unduly the electric locomotive, let us say that the efficiency of conversion, and the loss in the mains is 80 per cent. This would leave us with savings in the amount and cost of fuel of 3·6 to 1 and 5·6 to 1, respectively, in favour of the electric locomotive.

Batteries.—I consider that one would be quite safe in taking the life of lead cells to be about 3 years, and of nickel-iron batteries at least 7 years. While the cost of the nickel-iron battery is very much greater than that of lead batteries, I find that the nickel-iron is the more economical when capitalized over 6 or 7 years. In addition, the nickel-iron battery has several other advantages.

Another very important point is the charging of the battery, and its ability to run a shift without charging. It is not, however, necessary to let the battery run down until it requires to be completely re-charged, but it can be partially charged at such time as the locomotive is idle. It is quite practicable to install a battery to give, with the types of cell now manufactured, an effecive output of 170 kWh on a 2-axle locomotive. It follows, therefore, that a 2-axle electric locomotive will do the work performed by a steam locomotive consuming up to nearly 1 ton of coal per shift, and will do this work without any boosting.

These remarks apply to battery locomotives weighing from 15 to 20 tons (adhesive weight), as compared with steam locomotives of the 4-coupled type weighing about 25 tons. I am in possession of information showing that the average locomotive of the above type does not consume nearly 1 ton of coal per shift. A batch of 14 steam locomotives which I have in mind consume only 8 cwts. of coal per locomotive per shift; but to be on the safe side we may add 25 per cent to this figure and call it half a ton. Under these conditions the locomotive will do nearly two shifts without boosting.

The same remarks again apply to the 4-axle double-bogie electric type weighing up to 35 tons, as it is possible to put double the battery capacity on a double-bogie as on a single-bogie locomotive.

Cost of maintenance.—I have previously quoted the figures given by Sir Vincent Raven for the maintenance of two straight electric locomotives. For a battery locomotive it is of course necessary to add to these figures the cost of maintenance of the battery.

Running costs.—The total cost for oil, grease and waste and cleaning materials for 16 months of an electric locomotive doing shunting work, running 700 miles and performing 35 000 ton-miles of shunting work, was £1 10s. Distilled water for the battery cost £1 12s. These two items covered the whole of the running costs, exclusive of wages.

Repairs and renewals.—Of the electrical equipment no renewals of any description were necessary, the only repair being an ammeter lead.

Of the mechanical parts, the brake shoes have been renewed once, at a cost of £4 10s. The wear of the brake shoes has since been much reduced by a more extended use of the rheostatic brake.

Battery.—The Chloride battery is guaranteed for two years, and after 16 months it shows no falling off, either in capacity or efficiency, and this is borne out by the fact that it will still work over its full range. The original setting of the ampere-hour meter fixing the proportion of the charge ampere-hours to discharge ampere-hours has not been altered.

The average annual cost of a standard 2-axle battery locomotive weighing 17 to 20 tons, as compared with steam locomotives of 22 to 25 tons, has been well within £15 per year for all maintenance costs, including repairs and small stores, such as oil, grease, etc.

THE MEASUREMENT OF FLUX DENSITY IN THE AIR PATH MAGNETIC CIRCUIT.

By W. P. CONLY, B.Sc., Student.

(ABSTRACT *of paper read before the* SOUTH MIDLAND STUDENTS' SECTION, *7th March*, 1922.)

SUMMARY.

A new form of magnetic balance has been devised for the accurate measurement of the intensity of field at any point in the air path of a magnetic circuit, the instrument being sufficiently delicate to detect differences in intensity of field amounting to one line per square centimetre, whereas existing methods measure only the average intensity over the whole field, or are only sensitive to differences of 150 to 200 lines/cm².

The distribution of the lines of force issuing from the sides of a bar magnet has been plotted and the surface of the magnet discovered not to be an equipotential surface.

Biot-Savart's law has been experimentally proved.

Attempts to measure with accuracy the flux density in the air path of a magnetic circuit have met with little practical success. There is an increasing necessity for more exact measurement of flux density in air.

The following well-known methods are in general use for measuring this quantity:—

(1) Flux meter method.*
(2) Faraday disc method.
(3) Bismuth spiral method.†

(1) The flux meter actually measures only the flux issuing from an electromagnet where the exciting current may be rapidly reversed.

In modern instruments the scale has 50 divisions on either side of zero. The linkage for one scale division is of the order of 10 000 maxwells. Thus it may be seen that if the pilot coil is composed of 100 turns of fine wire and if the flux in the magnet is reversed, then 1 scale division $= 10\,000/(2 \times 100) = 50$ lines.

Owing to the very slight controlling force acting upon the instrument the periodic time is of the order of 1 minute, so that it is very difficult for an observer to read the deflection to within 3 or 4 scale divisions without much practice. This means that under the above conditions it is difficult to read the total flux to within 150 to 200 lines, i.e. 6 to 8 per cent of the maximum.

In addition to these sources of error the flux meter is not accurate unless the resistance of the circuit containing the coil is maintained constant at the value used when it was calibrated, and this is seldom the case.

The following mode of procedure may be used for measuring the strength of the field of a permanent magnet.

The pilot coil is placed between the poles of the magnet, the plane of the coil being normal to the lines of force, and the deflection of the flux meter noted when the pilot coil is jerked away. This method, however, besides being clumsy, has a disadvantage in that it is difficult to ensure that only that flux which threaded it in its initial position is cut by the pilot coil.

(2) In the Faraday disc method a disc of copper is rotated at constant speed between the poles of the magnet the flux of which is to be measured, a brush being in contact with the spindle of the disc and another with its periphery. The voltage generated will depend upon the field strength and speed, as in any other type of dynamo. The speed being known, the field strength can thus be deduced. This method is liable to give inaccurate results, owing to mechanical difficulties.

Both the flux meter and the Faraday disc merely measure the total flux in a portion of the magnetic circuit, i.e. the sum of all the flux densities over a definite area. The flux density is then obtained from the expression;

$$\text{Flux density} = \text{Total flux/Area of path}$$

This is merely an average flux density and, although approximately correct for the iron portion of the magnetic circuit, it is not representative of the true flux density at any part of the air path. In the centre of the air-gap the lines of force are grouped together, whilst towards the edges they are dispersed and a fringe is formed so that considerable variations from the average are actually present but are not recorded by the method of measurement.

From this point of view the bismuth spiral is superior to both the previous methods as it measures the actual intensities at any point in the field. This method follows upon a discovery made by Hall in 1880, that if certain metals are placed in a strong magnetic field their resistance changes. The greatest effect is obtained with bismuth.

If the resistance of a strip of bismuth be taken before it is placed in the magnetic field, and the rise in resistance noted after it is so placed, the field strength may be calculated. Because of the very small increase of the resistance with a large increase of field, a change of field intensity of less than 1 000 lines/cm² cannot be measured.

Any instrument for measuring intensity of field must, to meet modern requirements, be capable of measuring not merely the real intensity from point to point in the field, but also minute differences in intensities, e.g. 50 lines/cm². Such an instrument has been

* *Société Française de Physique*, Séances, 1904, p. 27, and *Electrician*, 1906, vol. 56, p. 560; also *Journal de Physique*, 1904, vol. 3, p. 696.

† *Comptes Rendus*, 1886, vol. 102, p. 358.

constructed, based on the principle of balancing by a weight the force deflecting a short conductor placed in a magnetic field.*

The author has lately constructed a new form of magnetic balance based on this principle, and this is illustrated in Fig. 1. A long balance arm of ash, AB, is delicately balanced by means of a pair of knife edges P in V grooves in the top of a brass column. At one end of the beam A is fixed a search coil consisting of 10 turns of silk-covered wire. This search coil is bent in the arc of a circle of radius $r =$ OA, the sides α and β being parallel. The side γ is 1 cm long and radial. The two ends of this coil are carried along the beam and connected by means of two copper spirals S, S_1 to two terminals on the insulated collar E. These spirals are made of the finest wire which will carry 1 ampere and are rolled flat and annealed in oil, and they are placed as close together as possible without danger of touching. These precautions are necessary as it is essential that any tension or compression of the spiral shall have only a negligible effect upon the movement of the arm.

field of unit strength (i.e. 1 line/cm^2) with a force of 1 dyne. The search coil consists of 10 turns. Thus if a current of 1 ampere flows round this coil in a certain direction, and the magnet has a field of unit strength, the length γ of 1 cm is pulled downwards in a direction normal to its length with a force of 1 dyne. If weights are placed in the scale pan the arm can be brought back to zero. Thus the mass in the scale pan will give an indication of the field strength of the magnet. Now, since 1 mg weight $= 0\cdot981$ dyne, if the ratio OA/OB $= 0\cdot981/1$ then 1 mg in the scale pan will counteract the force of 1 dyne on the arm γ. Therefore if 1 mg on the scale pan is necessary to bring the spot back to zero position on the scale, the permanent magnet has unit intensity of field, i.e. 1 line/cm^2.

It might, however, be argued that the portion of the limbs α and β in the magnetic field also carry a current and will also be deflected, but a closer examination will show that as these arms are parallel to one another, and as the current flowing along them is in relatively opposite directions, the effect of one counter-

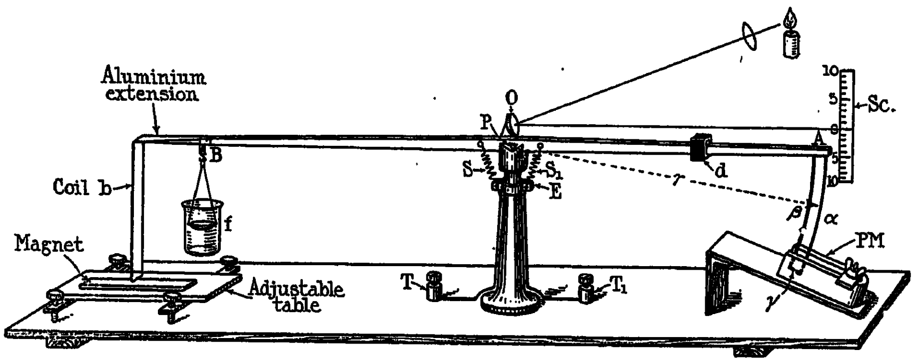


FIG. 1.

The terminals on the insulated collar are connected to two terminals T, T_1, on the baseboard. At the point B on the other arm is hung a light aluminium scale-pan upon a pair of knife edges. A rider, d, slides along the arm OA to enable a fine adjustment of balance to be obtained. Immediately above the central knife edges is firmly fixed to the beam a small mirror, so that the ray of light from the lamp is reflected on to the scale Sc. Thus any slight deviation of the balance arm from the zero position can be readily and accurately detected. A small glass beaker, f, is placed round the scale pan to act as an air damper. The permanent magnet to be tested, PM, is fixed to the baseboard in such a position that the flux to be measured threads the search coil, and the lines of force are normal to the plane of the coil. This permanent magnet must be in such a position that the radial arm γ of the search coil is always in the magnetic field when the balance arm swings. At the end B of the beam is fixed another coil, b, which will be referred to later.

From first principles, a wire 1 cm long carrying 1 C.G.S. unit of current is attracted or repelled by a

acts the other and the only tendency is for them to be forced apart until the coil encloses a larger area. This tendency is, however, counteracted by the rigidity of the coil itself.

The short length of coil at A also carries a current and it might be thought that a serious error would be caused by the mutual action between this current and the stray field of the magnet. It is found in practice, however, that as this portion of the search coil is remote from the air-gap of the magnet, the leakage flux and the resultant error are negligibly small.

The instrument just described was constructed in the electrical laboratory of the Birmingham University, and is now being used as a laboratory instrument. By its use changes of field strength of 1 line/cm^2 may be detected with ease. As an example of its sensitiveness it may be stated that during one test upon a magneto magnet with an air-gap of 4 cm, a small nickel coin was suspended in the air-gap between the search coil and one limb of the magnet. Although the difference in the reluctance of the magnetic circuit caused by this slightly diamagnetic object was so small as to be usually negligible, yet the instrument registered quite an appreciable difference. As the instrument is so sensitive it

* A. GRAY: "Absolute Measurements in Electricity and Magnetism," vol. 2, pt. 2, p. 700.

is absolutely necessary that the current through the search coil be perfectly constant and accurately measured.

The plane of the search coil must be absolutely at right angles to the flux in the air-gap, so that the maximum number of lines of force thread the coil. This may be accomplished by turning the magnet slightly until the scale registers a maximum deflection.

In the above-mentioned test it could be seen that the field was weaker in the centre of the air-gap than

Test to Find the Distribution of Magnetic Field along the Side and Edge of a Permanent Bar Magnet.

For this purpose a wooden wedge-shaped table is made, the surface of which is parallel to the search-coil arm γ when the balance arm is in the same position. On the surface of this table is glued fine emery paper to prevent the magnet from slipping. The table is placed in such a position that the distance from the

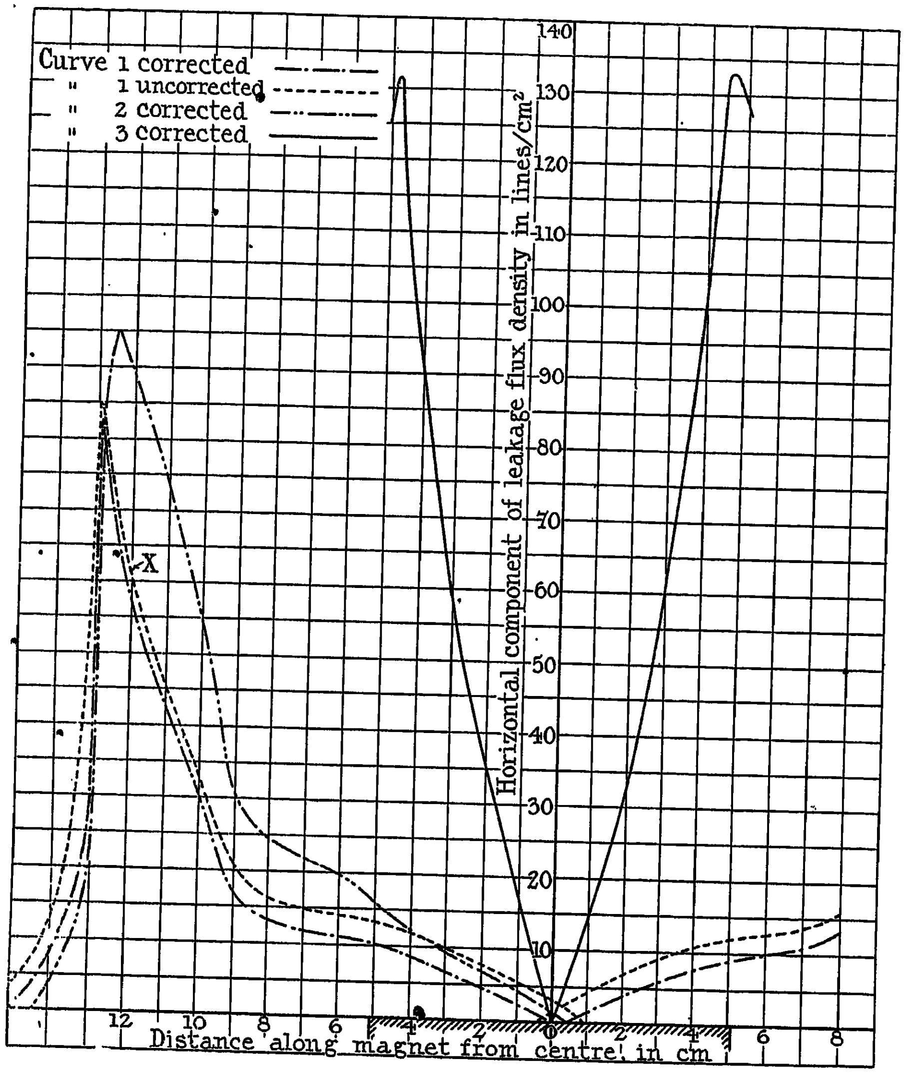


Fig. 2.

was near either limb, thus showing that the lines of rce spread out as they leave the magnet limbs, in e same manner as shown by the iron-filings method. Finer adjustments may be accomplished by placing ights in the scale pan until an approximate balance obtained, and then varying the current in the search il until the spot of light returns to the zero position. en the weight in the scale pan in milligrams, multied by the search-coil current in amperes, will give es/cm² direct.

arm γ to its upper surface when the instrument is balanced is half the width of the magnet. When the magnet is placed on its edge upon the table the arm γ lies along the centre line of the magnet and as near to it as possible without actually touching it. This arm γ now lies in the magnet field emanating from the magnet and is at right-angles to a certain component of that field. By passing a current round the search coil we can measure the strength of this component of the field in lines/cm² by the method described above.

If the lines of force leave or enter the magnet all along the surface at right angles, then the instrument reads direct in lines/cm^2 leaving or entering the magnet at the point under the seach-coil arm γ. The magnet can be slid up and down the table and a curve plotted showing the strength of field at every point along it. Fig. 2 shows such curves, curves 1 and 2 being attained for a magnet 25·5 cm long, 2 cm wide, and 0·5 cm thick. The abscissæ represent distances from the centre of the magnet, while the ordinates represent the strength of field emanating from the magnet at corresponding points. Curve 1 (not corrected) shows the readings along the side of a bar magnet.

The search coil, however, carries a current which produces around itself a magnetic field. Owing to the close proximity of the iron, the reluctance of the magnetic path of the field is affected. Since the tendency of any coil carrying a current producing lines of force is to move so that more lines will be embraced, the search coil moves down, thus covering more of the magnet. This downward movement is independent of the direction of the current, and can be taken as being constant all along the magnet as a low point on the saturation curve is being used. The value of this error, which might be called the "inductive effect," can be found for the working current of 1 ampere in the coil by replacing the magnet by a similar bar of unmagnetized steel. The inductive effect must be subtracted from the curve of field intensities. There is, however, another error which is not independent of the direction of the current, i.e. the error due to the earth's field, and its value may be determined by removing the magnet and reversing the current in the search coil. This error must be added to the uncorrected curve on one side of the centre and subtracted on the other. Thus a corrected curve is obtained of the flux density emanating from the side of a bar magnet, assuming that the surface of the magnet is very nearly equipotential.

In Fig. 2 at the point marked X there is a pronounced kink in the otherwise regular curve. This is probably due to the fact that at this point there is a slight "soft spot" in the magnet. The material at this spot being more permeable, a greater proportion of the lines of force due to this spot flow along the axis of the magnet, and a smaller proportion flow out at the side as leakage.

Curve 2 shows the corrected distribution along the edge of the same magnet. It is to be noticed that the intensity of field up to about 9 cm from the centre is far greater than is the case along the side of the magnet.

Curve 3 shows the case of a short bar magnet 4 in. × ½ in. × ½ in., where every care was taken in hardening and magnetizing the magnet to keep it homogeneous and uniformly magnetized. The magnetic moment of this magnet (found by the tangent galvanometer and vibration magnetometer method) is 1 377 dyne-cm.

Up to this point it has been assumed that for all practical purposes the flux along a bar magnet is normal to the surface. This being the case, the above curves, which actually represent the component of magnetic field normal to the surface, become curves representing the total intensity of field at any point along the magnet. To find how far this assumption is correct another test is required.

An aluminium extension, the length of which is adjustable, is fixed to the scale-pan end of the beam, and on the end of this extension is rigidly fixed a long rectangular search coil. The plane of this second coil, b (Fig. 1), is such that the length of the beam is normal to it. The length of this extension and the width of the coil are such that if the coil be placed in a field of 1 line/cm^2 and 1 ampere flows round the coil in such a direction that the coil is repelled, then 1 mg in the scale pan brings it back to its normal position.

A table of adjustable height is placed under this second search coil, upon which the magnet is laid. If in the position shown in Fig. 1 the lines of force leave the surface at an angle θ, there will be a component $H \cos \theta$ of the lines of force tending to move the balance. If a current of 1 ampere flows in the search coil this force can be counterbalanced by putting weights into, or removing weights from, the scale pan. If there is no pull, then $\cos \theta = 0$, i.e. all the lines leave the surface at right angles.

Due, however, to the inductive effect of the search coil, a constant and known force must be applied to the remote end of the balance to tear the coil away. Measurements may be made by placing an assortment of weights in the scale pan, and then balancing these weights by means of the adjustable rider when the current is switched off. As the current of 1 ampere is now being caused to flow round the search coil, the force of attraction may be measured by taking weights out of the scale pan until the balance arm moves. This force of attraction consists of the resultant of the following three forces:—

(1) Force due to the inductive effect.
(2) Force due to the earth's field.
(3) Force due to the horizontal component of the magnetic field.

Forces (1) and (2) being known, the horizontal component of the magnetic field of the magnet may also be determined.

In practice it is found that the horizontal component is so small that it is impossible to weigh it except at the extreme ends of the magnet, in fact so small that for the purpose of determining the distribution of field intensity the lines of force may be taken as issuing at right angles to the surface of the magnet.

Proof of Biot-Savart's Law by Means of the Magnetic Balance.

Let a wire AB carry a current I; then the force on a unit pole placed at any point P due to a short elemental length of conductor $= df$,

$$df = \frac{I \sin a \, dx}{y^2}$$

where $dx =$ elemental length of wire AB;
$y =$ distance from P to dx at any instant; and
$a =$ angle between Pdx and wire at any instant.

(This is generally known as Biot-Savart's law, but was originally stated by Laplace.)

Multiplying numerator and denominator by $\sin^2 a$ we obtain

$$df = \frac{I \sin^3 a dx}{y^2 \sin^2 a}$$

Now $$r = y \sin a$$

where r is the perpendicular distance from the point P to the conductor; and the perpendicular cuts the conductor at C,

therefore $$df = \frac{I \sin^3 a dx}{r^2}$$

But $$x = r \cot a$$

where x = length of wire from C to dx.

Substituting da for dx we have

$$df = \frac{-I}{r} \sin a da$$

$$F = \frac{-I}{r}\int_{\pi/2}^{a} \sin a da \text{ (where } x\text{=CA and } a\text{=angle CAP)}$$

$$F = \frac{I}{r}\left[\cos a\right]_{\pi/2}^{a}$$

$$= \frac{I}{r} \cos a$$

$$= \frac{I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}}$$

If length CB = CA, then force F on unit pole P due to whole length AB

$$= \frac{2I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}} \quad . \quad . \quad . \quad (1)$$

Thus for a wire of infinite length

$$F = \frac{2I}{r} \cdot \frac{\infty}{\sqrt{(r^2 + \infty^2)}} \text{ (for the whole length of wire)}$$

$$= \frac{2I}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

It is possible by means of the magnetic balance to demonstrate whether this formula holds good in practice. It is, however, impracticable to measure the force of attraction between two wires carrying a current when placed a distance r apart; it is the force of repulsion which must be measured.

We have found that the force upon a unit pole placed at a distance r from a wire of infinite length and carrying a current I is $2I/r$ dynes.

This formula is in general use and is frequently wrongly applied to the case of a wire carrying a current, irrespective of the length of that wire. It has been previously shown that for a wire of definite length $2x$ carrying a current I the force upon a unit pole placed at a distance r from it is

$$\frac{2I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}}$$

By means of the balance the error caused by using formula (2) in place of formula (1) in the case of a wire 12 cm long has been found. The wire carried 50 amperes, and the search-coil arm was placed at a distance of 1 cm from it.

For the purpose of experimentally proving Biot-Savart's law coil b (Fig. 1) is used as in Fig. 3. The lengths of the two arms of the beam are such that if the width of this coil be 0·844 cm, then 1 dyne per cm length is balanced by 1 mg in the scale pan. In Fig. 3, AEFB represent the movable search coil; EF is bisected at O″; AB is bisected at O′; and CD is a wire 160 cm long. This length is such that leads connected to the ends of the wire do not appreciably affect the balance whilst carrying a current. The remote ends C and D of this wire are soldered to wire stretchers which keep it taut, and these slide up or down slots in the end brackets for altering the distance between the wire and the coil. A fine adjustment is made in this distance by means of a brass differential jack J fastened to the baseboard, whilst the inner screw of the jack is secured to the wire but insulated from it.

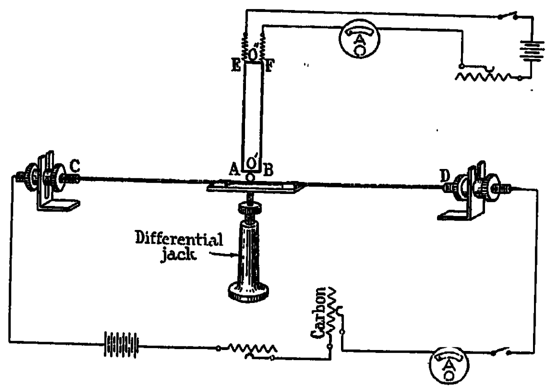


FIG. 3.

A steady current of 1 ampere is maintained in the search coil while currents varying from 0 to 150 amperes are sent along the wire CD. The leads from the search coil circuit are plaited together and taken to some remote distance before being connected to the ammeter and other apparatus, in order that they shall have no effect whatever upon the reading of the balance. For the same reason the leads from the wire are carried away as far as possible.

As the instrument is highly sensitive, extreme care must be taken. During recent experiments with this balance a mysterious inconsistency in results was definitely traced to the fact that the operator was carrying a thin steel nail-file in his pocket.

The theoretical force of repulsion may be calculated by means of formula (1) and compared with the result obtained in practice.

The arm AB (Fig. 3) is repelled by CD, but the arm EF carrying a current in a relatively opposite direction is attracted.

Let a force of repulsion be taken as positive, and let a force of attraction be taken as negative. The algebraic sum of the forces gives the resultant force. The effect of CD upon EA is balanced by the effect of CD upon FB.

Calculation of the force upon the search coil.—

Let
$$AB = EF = 0\cdot844 \text{ cm},$$
$$FB = EA = 11\cdot4 \text{ cm},$$
$$OO' = r = 1 \text{ cm},$$
$$CD = (OC + OD) = 160 \text{ cm}.$$

CD carries 50 amperes = 5 C.G.S. units.

(*a*) *Force on AB due to CD.*—According to the above theorem the field strength at the centre O′ of the coil side AB due to a current of I amperes in CD would be

$$\frac{2I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}}$$

where x = CO = OD, and r = OO′.

Owing to the displacement of any point on AB other than O′ the field strength will be a little different from the above, but calculation shows that these differences are so small with lengths such as AB and CD that they may be neglected, and the field strength along AB may be regarded as constant.

Thus
$$f_0 = 2\frac{5}{r_0} \cdot \frac{x_0}{\sqrt{(r^2 + x^2)}} \quad (\text{where } r = 1 \text{ cm}, \; x_0 = 80 \text{ cm})$$
$$= 10 \times \frac{80}{\sqrt{(1 + 6\,400)}}$$
$$= 10 \text{ dynes per cm length (approx.)}$$

(*b*) *Force on EF due to CD.*—

Force on
$$Q'' = -2\frac{5}{12\cdot4} \cdot \frac{80}{\sqrt{[(12\cdot4)^2 + (80)^2]}}$$
$$= -\frac{10}{12\cdot4} \cdot \frac{80}{\sqrt{(133\cdot76 + 6\,400)}}$$
$$= -\frac{10}{12\cdot4}\left(\frac{80}{80\cdot93}\right)$$
$$= -0\cdot796 \text{ dyne per cm length}$$

The total resultant force on the coil is $+10 - 0\cdot796$, or $9\cdot204$ dynes per cm length.

Fig. 4 shows curves connecting current in amperes with dynes per cm length, or weight in milligrams in the scale pan. Three sets of curves are shown and all are straight lines, proving that the force is directly proportional to the current. Dotted lines show calculated curves, while full lines show curves obtained from the readings of the magnetic balance.

Sources of error.—In all three cases there is a very slight deviation between the calculated curves and those obtained from the readings, but these inconsistencies can be accounted for.

Take as an example the case where $r = 0\cdot75$ cm. It will be noticed that the calculated curve falls slightly above the curve given by the instrument (the measured curve).

There are several causes which would account for this. It is very difficult to measure exactly the distance between the centre of the wire and the centre of the arm AB. Two more calculated curves are drawn for $r = 0\cdot7$ cm and $0\cdot8$ cm, respectively.

The measured curve falls well between these limits, so that an error of much less than $0\cdot25$ mm in this measurement would give rise to this error in the measured curve.

Besides the difficulty of measuring the correct distance from centre to centre of wire and coil side the following sources of inaccuracy also arise:

(1) It is almost impossible to ensure that the corners at A and B are exactly square, so that the effective length of the arm AB may be shorter than its apparent length.

(2) The arm AB may not be exactly parallel to CD.

A dotted line is drawn showing the effect produced if the projected length of the arm AB upon the wire CD = 0·83 cm. It is found that this dotted line almost coincides with the measured curve, showing that the latter would coincide with the calculated curve if,

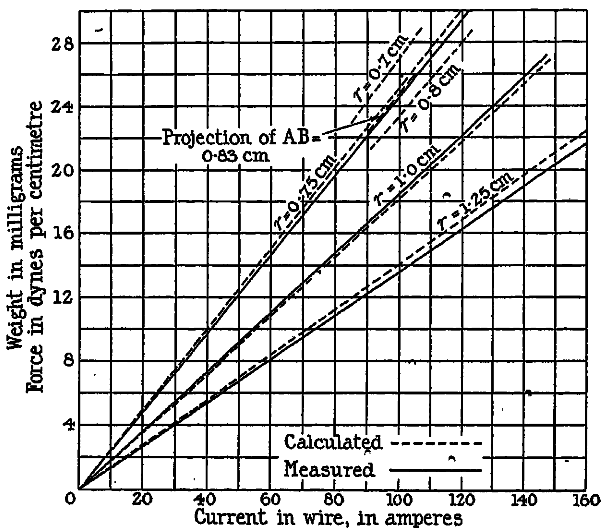


FIG. 4.

owing to either source of in accuracy given above, the projected length of AB upon CD = 0·83 cm.

Although every care was taken during the experiments to avoid such errors, the methods of measuring lengths such as AB and r do not admit of an accuracy compatible with the sensitiveness of the instrument, but the result appears to afford good evidence as to the validity of the expression

$$F = \frac{2I}{r} \cdot \frac{x}{\sqrt{(r^2 + x^2)}}$$

The author is greatly indebted to the University of Birmingham, where he was given every facility for carrying out the experiments necessary for this paper. He is particularly indebted to Professor W. Cramp, D.Sc., who so kindly allowed him to be his assistant in his research upon magnets and whose untiring advice and guiding hand made this work possible.

ELECTRICITY AS APPLIED TO MINES.

By J. C. Stewart, Student.

(Abstract *of paper read before the* Scottish Students' Section, *10th March*, 1922.)

Summary.

The paper deals in a very general way with the use of electricity in collieries. The types of generators, motors and cables are explained, and the factors governing the use of each particular type are discussed.

A brief outline of the mechanical plant used in conjunction with motors is given, including pumps, haulages, coal cutters and winders.

Diagrams are given of a typical haulage, as used extensively in this country, a turbine pump, a disc coal cutter and a small electric winder.

Introduction.

For the past few years the ordinary individual has had brought to his notice phases of industry which before he was wont to regard as necessary but noxious. This applies very truly to the coal industry. More recently the eyes of the community were focussed on the coal mines and a more general knowledge of the mining industry and its absolute necessity to the life of this country was then gained. In the present period of economic unrest and bad trade every industry is trying earnestly to cut down costs and increase efficiency, and in this project they have no better ally than electricity.

But for electricity, coal mines would be of no value to us. Since the earliest days of coal mining the use of machinery has slowly but surely ousted purely manual labour, as in most other industries. The problems presented by winding, pumping, ventilation and haulage have been very gradually solved to the satisfaction both of engineers and workers.

Twenty years ago the use of electricity was confined to lighting on the surface and to long-distance underground signalling with batteries. To-day there is not a single instance in the application of power where electricity has not been employed, in most cases successfully.

By far the greatest number of collieries have direct-current installations, owing to the fact that the common load in pre-war days was in the neighbourhood of 300 kW and an installation of this kind is cheaper with direct than with alternating current. The tendency at the present time is, however, where possible, to take a bulk supply; where the power companies have not run mains and where there is a fairly big demand for power, turbo sets up to 5 000 kW have been installed.

Voltages vary from 80 to 550 with direct current and from 400 to 6 600 with alternating current, and periodicities with the latter are 25, 30, 40 and 50.

Generally speaking, an a.c. system is to be preferred to a d.c. system. With the former, it is easier to comply with mining regulations if the mine is liable to gas. Direct-current motors, on the other hand, are more liable to open sparking and for this reason in fiery mines they have to be totally enclosed. This is practicable up to about 40 h.p., but above this the overall dimensions become abnormal.

In the case of a.c. motors, enclosure is necessary only at the slip-rings, while squirrel-cage motors can be left open.

An ideal system is a combination of both alternating and direct current, but this is not always possible.

Motors.

All types of motors in use for industrial purposes are, generally speaking, employed underground; they are modified, however, to suit the conditions. The overload capacities are extended, for the motors may have to be explosion-proof and withstand damp atmospheres.

Again, although laid down in places where they will be protected, they encounter troubles not associated with surface plants. The men in charge cannot always make systematic and regular visits to all the motors, as in some cases they are so widely distributed, and the attendants are usually kept busy with actual repairs.

In fiery mines or those liable to gas, motors and switchgear must be flame-proof to lessen the possibility of danger from explosions by sparking. Mining regulations are becoming very stringent in this matter and it is not always permissible to install electrical plant where the possible danger from gas is very great.

To overcome this, the inclination is towards the use of alternating current, when the risks from open sparking are considerably lessened. Motors are placed, where possible, in intake airways, i.e. where the fresh air is entering.

Switchgear.

In common with motors, mining switchgear when underground follows the lines of ordinary switchgear. The same laws governing the installation of motors apply equally to switchgear. Switches have large machined faces where joints occur, are as far as possible fool-proof, and must have plenty of space inside, to lessen any risks of short-circuits or earths caused by damp or deposit.

The human element, in a great many cases, is largely responsible for the success or failure of electrical plant underground. The man in charge of, say, a haulage or a coal cutter is usually more concerned in keeping up his production than in shutting down for the electrician to repair any small trouble, and this usually leads to more serious breakdowns.

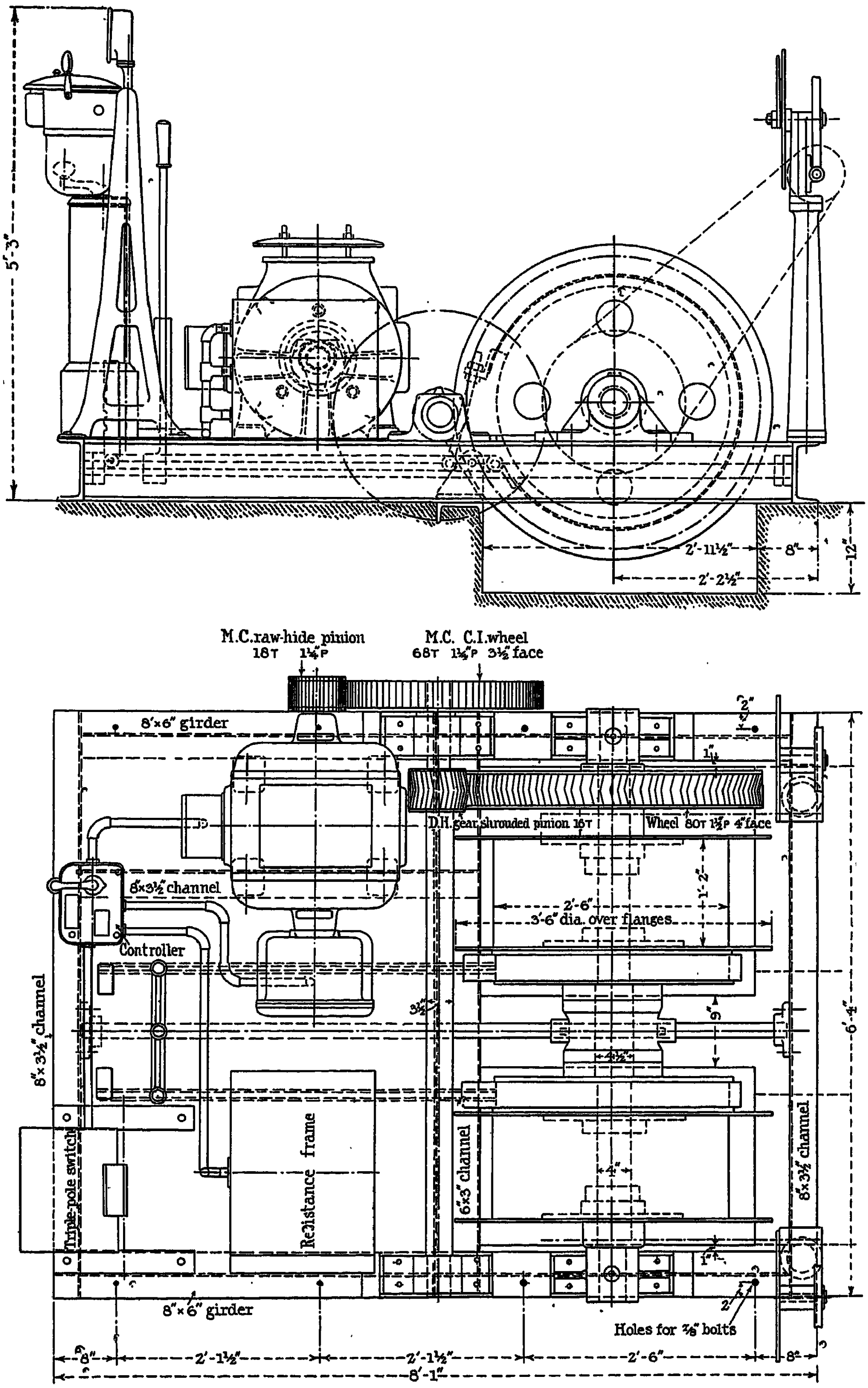


FIG. 1.—Arrangement of 250-h.p. main-and-tail haulage.

Pumping.

In all the uses to which the motor has been put in mining, no better results have been obtained than in the driving of pumps, as they have to operate in some cases where no other power than electricity could be used efficiently. Both reciprocating and turbine pumps are in use for mine drainage, but of late years the turbine pump has become more prominent, the determining factor for this being largely the small amount of space occupied and the advent of multi-stage pumps. The time is past when turbine pumps were considered suitable for low lifts only, as any required head can now be obtained.

A brief description of both types of pumps would perhaps be appropriate here. A reciprocating pump consists of three separate single-acting plunger pumps connected to common suction and discharge pipes. The cranks on the shaft are placed 120° apart, so that the discharge is practically continuous. Occasionally, however, separate suction and discharge pipes are built with the pump, so that if one plunger pump breaks down it is possible to carry on with the other two until repairs are effected. The speed of the rams varies from 35 to 60 ft. per minute, and to obtain this the motors require to be geared down.

The turbine pump is made up of a series of single-stage centrifugal pumps. Each rotating disc or impeller has its own chamber. The water, after leaving the first impeller, passes through a guide port to the second, and so on until it reaches the delivery column. The head generated depends upon the peripheral speed and diameter of the impellers, the best speeds being from 1 000 to 3 000 r.p.m.

For turbine pumps, alternating current is to be preferred for high speeds and large horse-powers, but there are quite a number of direct-current motors running up to 1 800 r.p.m. which is about the limit, as commutation troubles become considerably increased at higher speeds.

The limiting feature with direct current is, as mentioned above, the necessity for enclosing a motor on account of gas in the mine. To avoid this, it is usual to install two or more pumps of smaller capacity and divide the total lift into two or more stages.

With alternating current, squirrel-cage motors are much used, and it is not an infrequent practice, where there are large quantities of water to be dealt with on a fairly high head, to install high-tension or even extra-high-tension motors for driving pumps.

Haulages.

The conveying of material from the coal face to the bottom was a problem which until recent years was not satisfactorily solved. The advent of larger electrical installations, however, has resulted in a marked tendency towards electrical haulage for the large plants on the surface, while for secondary haulages underground electricity has, of course, no rival.

The methods of haulage may be divided into the following: Direct-acting haulage, main-and-tail rope haulage and endless-rope haulage. To this might be added endless-chain haulage and haulage by locomotive, although these latter do not find much favour in this country.

The features determining which type shall be used are the circumstances existing at each particular colliery, and it is quite common to find more than one system in operation at the same colliery.

In the direct-haulage system, the motor and haulage gear are placed at the top of the incline, the full hutches are drawn up the incline by the haulage, and the empties are afterwards run back down the gradient, carrying the rope with them. The inclinations must be sufficient to ensure this, e.g. up to 1 in 20, and must be fairly uniform. One line of rails is used, though a double-drum haulage and double rail can quite well be used. The average speed is about 6 m.p.h.

The main-and-tail haulage is generally used on varying gradients, where it is necessary to haul the hutches both inbye and outbye. Two drums are used, both being fixed to the same shaft and driven by clutches, one carrying the main rope and the other the tail rope. The load of full hutches is drawn out by the main rope, the tail rope being fixed behind the rake. Both drums revolve at the same time, one being driven by the motor direct and the tail drum being turned by the tail rope as it is drawn off. If the gradient at any part of the road favours the load, the main rope is detached and the load allowed to run forward by gravity, but controlled by the brake on the tail drum. When the load is brought out, empty hutches are attached and hauled inbye with the tail rope, the main rope being now used for the control. Speeds up to 10 m.p.h. are usual with this type.

The endless-rope or chain haulage has one chain or rope running over the entire system of both sets of rails, one set going in and the other out. The hutches are sometimes attached singly about 10 yards apart, and sometimes 8 or 10 of them are fixed on to the rope together.

Haulage by locomotive is so closely allied to tramway haulage or traction that it needs no description. It is greatly used in America where the inclinations of the seams are not quite so steep as in this country.

Motors for Haulages.

All types of motors are in use with haulages, depending, of course, on the system of supply. Whatever the type, it has a large overload capacity and a fairly high rating. Series motors are sometimes used, but compound-wound motors are most generally installed if the system is a direct-current one. In the case of an a.c. system slip-ring motors are usually the type most in favour owing to the large starting torque required.

The resistance coils on the starting gear must be capable of withstanding full-load current for several minutes, as in some of the roads with steep gradients there are bad bends to be encountered, and these necessitate the slowing down of the motor.

Coal Cutting.

The practice of working coal seams by machinery is one that has become necessary for several reasons. For instance, it is more profitable to work thin coal

seams by mechanical than by manual labour. The thickness of coal seams varies from 12 in. to about 6 ft., although there are few seams of the latter thickness left in Scotland. The average thickness is 24 in. and this is therefore the chief determining factor in the height of a coal cutter.

The length of face is usually about 100 yards, and this is split up by roads or gates every 10 yards or so. The cut is generally made under the coal to a depth of from 3 to 6 ft., and about 5 in. thick. Sometimes, however, better results are obtained by cutting in the coal if the underlying strata be too hard, and if the coal is very hard it is usual to cut in any soft band which appears in the coal. The coal is then parted from the upper strata by blasting or hand labour, filled into hutches and taken away. This method is known as the "long-wall" system of coal cutting.

Another method, largely used in England, is the stoop-and-room or pillar-and-stall system. This is only carried out where the coal seams are fairly thick, e.g. 4 ft. and upwards. In this method the coal is cut into rectangular pillars or stoops by stalls or rooms driven at right angles to each other, the pillars or stoops being afterwards taken out.

It is not possible to lay down hard-and-fast rules as to methods of working coal, as circumstances vary with each seam, and each particular stratum of coal has to be considered on its own characteristics.

At the present day there are three distinct types of coal cutters in successful operation, viz. the disc, the bar and the chain. The oldest of these is the disc machine, which might be described as an adaptation of the circular saw. The disc or wheel has cutting tools or picks fixed on its periphery. The disc is supported from the general body by a strong bracket so that the cutting portion projects to the required amount. The body of the coal cutter consists of a motor, gear-box for driving the disc, haulage drum and gear, and starting switch. These are all encased in strong steel boxes and mounted on skids or a base-plate extending the full length of the body. By reason of its general robustness and massive construction, this type of coal cutter is capable of doing harder work than the chain or bar type.

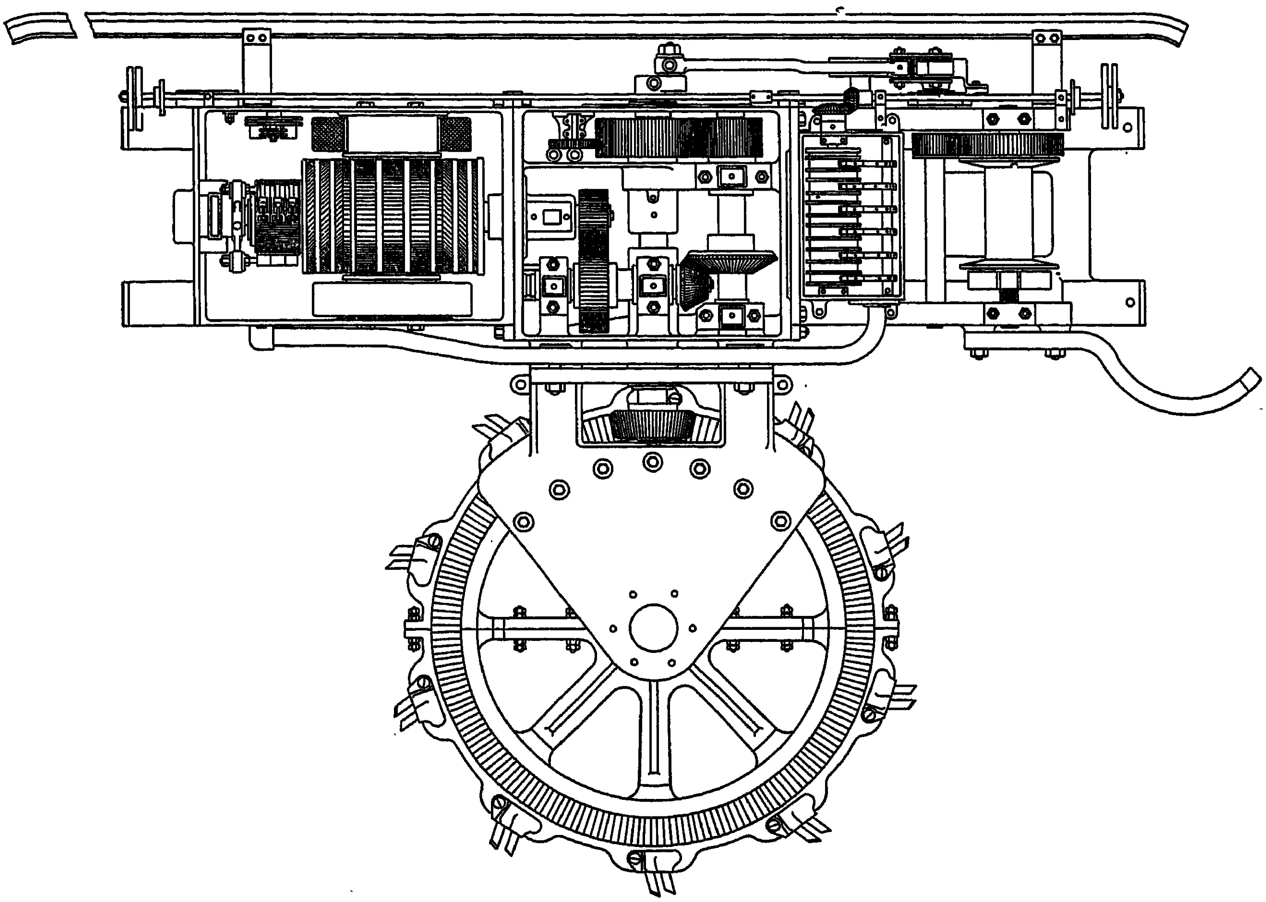


FIG. 2.—General arrangement of the "Crescent" coal-cutter; B type with d.c. motor.

Bar coal cutters differ from both the disc and chain types in their cutting action, in so much that the bar might be likened to a taper twist-drill in the threads of which picks have been fixed. To this bar is given a revolving, reciprocating motion. Due to this reciprocating motion, part of the holings work their way out

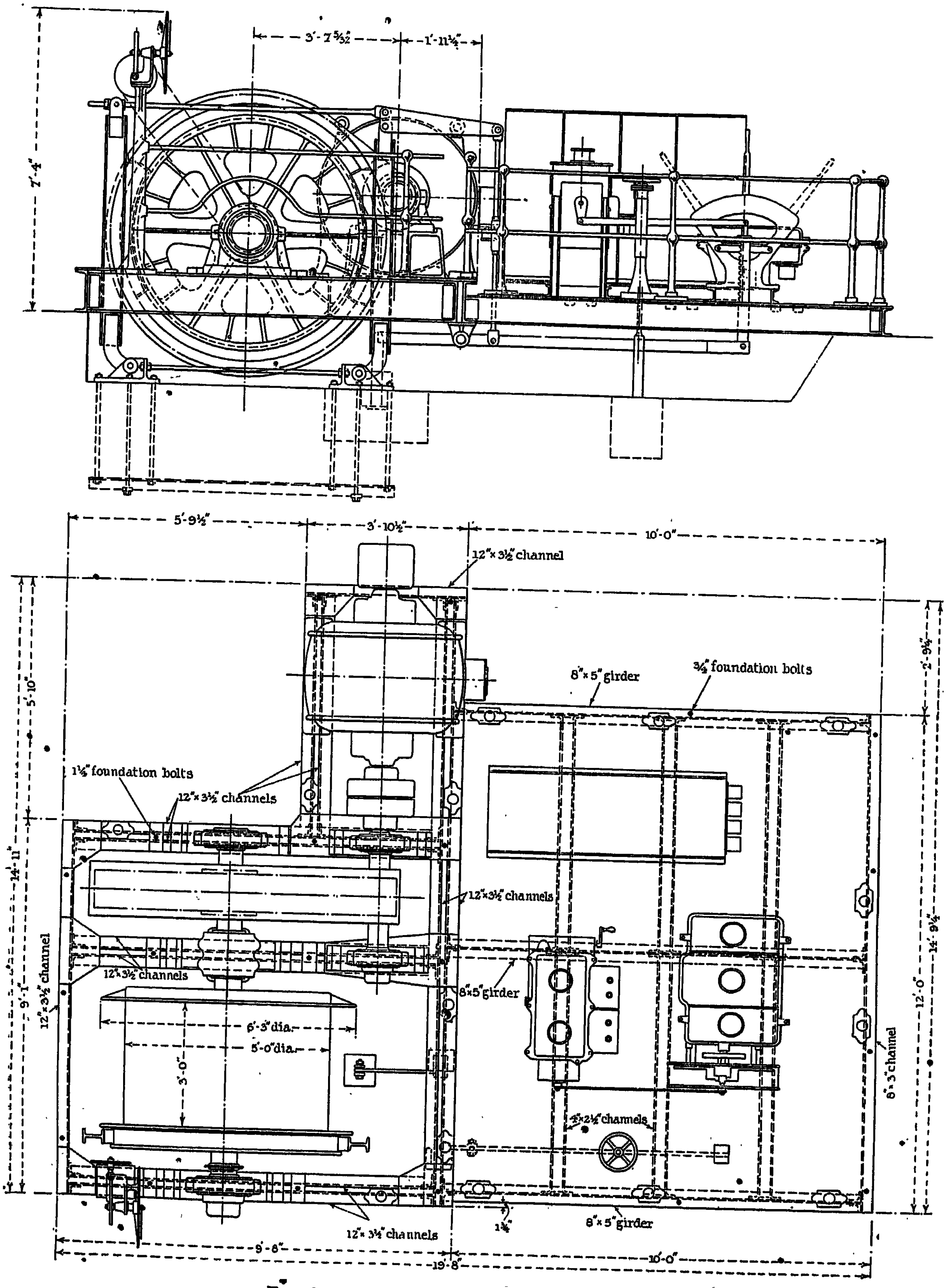


FIG. 3.—Arrangement of 150-h p. haulage gear.

along these threads. Where the coal is at all friable the bar machine gives wonderful results and a much higher speed can be attained by the actual picks.

Judging from old records, it appears that the chain machine claims priority for the number of patents taken out in connection with it. It has a jib carrying a heavy, case-hardened endless chain with a pitch of about 7 inches. The cutter picks are fixed in recesses in shaped cutter blocks on the chain, and are held in position by set-screws. The chain is carried round a sprocket wheel, the centre of which is hollowed out to form an oil reservoir for the wheel. The tension of the chain can be varied by an adjusting screw and the jib locked securely in position. Within late years there have been more of this type of coal cutter installed than of the bar or disc type, a fact peculiarly significant of the practice necessary in collieries at the present day.

Electricity was first applied to coal cutters about 30 years ago. Motors of from 10 to 12 h.p. were fitted, but the attempt was a complete failure, which is not surprising considering that motors of 28 to 40 h.p. are used to-day, and even these are not sufficient in some cases. The motors are, of course, of the totally enclosed type. For use with direct current they are four-pole and doubly compounded. Some makes have series fields which give them a very heavy starting torque, but the armatures all run about 1 000 r.p.m. and are geared down to the disc, chain or bar.

In alternating-current installations for smaller sizes of coal cutters, squirrel-cage motors are fitted and, for heavier machines, wound rotors. Due to the small amount of height permissible in coal cutters the armatures and rotor cores are very long with small diameter. In addition, a reversing switch is carried, and the starting switch and resistance are of heavy construction as they usually have to withstand a great deal of "inching."

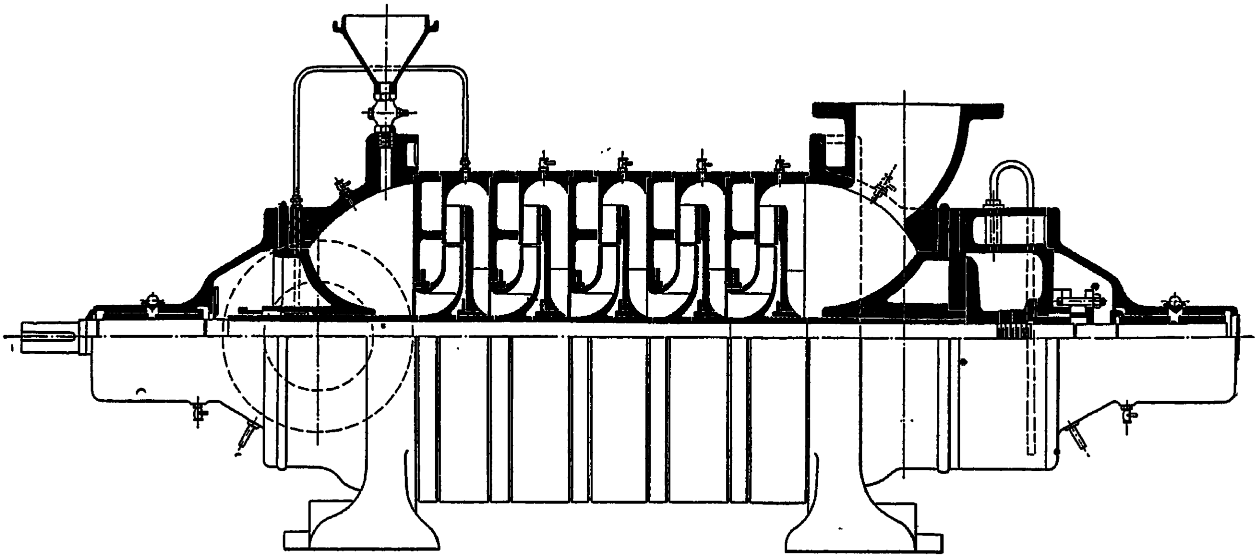


FIG. 4.—Sectional arrangement of multi-stage turbine pump.

Winding.

While there have been a number of cases where electricity has been applied successfully in place of steam, there is not the same chance for economy as in most other branches of mining work. Very little would be gained in most cases by substituting electricity, the chief difficulty being the large mass which must be started from rest, accelerated often to 60 ft. per sec. and brought to rest in less than 90 seconds. Added to this is the fact that the motor in a great many cases would be in the region of 1 000 h.p. and would have to compete against a steam engine applied directly to the work and in close proximity to the boilers.

In addition, the demand for anything up to 1 500 h.p. at short notice would be somewhat difficult to cope with, although the advent of super-stations would make this factor of little account. Despite this, electricity has been tried out in quite a number of cases and there are now both d.c. and a.c. winding installations. The motors are of the open type, running at normal speeds and controlled by heavy reversing switches, and have to be capable of severe overloads.

The main advantages of electric winding are that maintenance is considerably less than for steam, smaller pit-head frames are needed, and economical operation is obtained in the period taken by the colliery to reach its full output.

Ventilation.

This is the most permanent load of any in mining work and, for this reason, fans should all be electrically driven, in order to improve the net load factor of the plant. This is even more so at the present day when most collieries employ the smaller high-speed centrifugal suction or force fans very suitable for direct coupling to a motor, instead of the large Guibal fans of former days, which would require a large low-speed motor for their operation. Added to this is the fact that when a

colliery is first opened (and for several years afterwards) the full air delivery is not required, and electrically driven fans can be run at lower speeds without undue losses.

For ventilation work a.c. motors are preferable, although there is no reason why d.c. machines should not give satisfactory results. A synchronous motor is eminently suited for this work, as the load is constant.

Miners are gradually losing their fear of electrical breakdowns, and for this reason we may expect that in the future very few steam ventilating fans will be installed.

The three following applications of electricity in mines have now reached the stage where at least one of them has no competitor, the other two being impossible without electricity, viz. shot-firing, telephones and signalling.

For the first-named, a small magneto exploder is generally used, although some managers still favour a battery of cells. The magneto armature is hand-driven through gearing at from 2 000 to 3 000 r.p.m. at the moment of closing the firing key. Both low-tension and high-tension exploders are in use, and series connection ensures that no part is fired unless all the fuses are in order.

Telephone connection is now legally enforced between the generating station, pit head and pit bottom. The telephones are the same as in general commercial use, but care is taken to make them very strong and water-tight.

For signalling circuits large batteries are installed with a maximum voltage of 25. Enclosed pull-switches are installed every hundred yards, and thus any danger of open sparking is eliminated. Signals are indicated both visually and by means of a bell, so that the risk of receiving the wrong signal is checked. Arrangements are made to prevent confusion of signals, the signals being automatically returned to the sender so that mistakes can be rectified.

Lighting.

Both carbon and metal filament lamps are used for lighting the pit bottom and for 100 yards from the bottom, but at the face Davy lamps still predominate. A recent report showed that there were 4 300 electric hand-lamps and 720 000 oil hand-lamps in use.

The efficient lighting of working places underground helps to increase both the output and the safety of working. Electric hand-lamps consist of an aluminium case in which is a lead storage cell. The lamp itself is further protected by a thick glass cover. The casing is so arranged that if the outer glass cover is broken the lamp is automatically extinguished. The Home Office regulations require that at least 1 c.p. must be given after 9 hours' continuous burning.

There are various makes in use, but they differ very little in principle. The usual weight is about 4 lb.

The objection that electric lamps give no indication of fire-damp has been overcome by the introduction of various fire-damp detectors. One make gives indication of as little as 0·25 per cent of gas.

Miscellaneous.

One other piece of machinery largely in use in collieries now-a-days is the shot drill. This consists of a rotary drill driven by a 4 h.p. motor, and the whole carcass is fixed on wheels so that it can be moved quickly from place to place.

These machines are used chiefly for drilling holes in the coal after it has been cut by the coal cutter. In these holes are placed explosive cartridges which are fired, the coal consequently being blown down.

The following are some figures in connection with a fairly large colliery in Scotland, and these figures are fairly typical for the whole of Scotland:—

Output per week	8 200 tons
Consumption per week	67 000 units
Water used per week	32 000 tons
Water per ton of coal	4 tons
Consumption per ton of coal	8·2 units
Average load factor	44 per cent

The overall output is 6·5 lb. of coal per unit generated.

HYDRO-ELECTRIC POWER SUPPLY.

By A. Tustin, M.Sc., Student.

(Abstract *of paper read before the* North-Western Students' Section, *14th February*, 1922.)

Summary.

The objects of the paper are: (1) To describe briefly the chief constituent parts of a hydro-electric development, and their functions; (2) to discuss some of the economic factors controlling the development and operation of water-power plants; and (3) to consider the question of tidal power where it exemplifies the working of these economic factors.

Types of Development.

A stream of water, in which Q lb. of water per second flow so that they fall through a vertical head of H feet, necessarily loses QH ft.-lb. of potential energy per second. In the state of nature this is turned into the kinetic energy of irregular motion, and by fluid friction into heat. The task of the water-power engineer is to reduce fluid friction by guiding the water into a uniform stream-line flow, and abstracting its energy by means of water turbines.

A given power may be provided either by a small stream of water falling through thousands of feet, or by an immense mass of water falling through a few feet. There is no real difference between the principles by which the water-power engineer deals with the one or the other, but naturally they lead to plants widely differing in engineering structure and appearance.

No two water-power stations are identical, owing to local geography, the power available, and the constant progress in technique; but for descriptive purposes we may distinguish two characteristic types of plant, i.e. low-head plants of the dam or barrage type, and higher-head plants of the pipe-line type. The two merge into each other.

In the dam type the power house itself is built across the river so as to form a dam; or part of a dam. The water rises on the up-stream side, and is allowed to flow through turbines in the power house under the head so obtained.

In the pipe-line type the water is accumulated in a catch pool at a higher level, and is brought down to the power house by a pipe or pipes, which may be miles long.

Pressure Pipe or Penstock.

The design of pipe lines for hydro-electric work presents a very varied series of problems. There is a wide choice of material: riveted boiler plate, reinforced concrete, wood staving, cast iron, welded steel and weldless steel all being met with.

The number, size and location of the pipes must be determined, and due thought given to the questions of anchorage, temperature expansion, water-hammer effects, and mechanical strength, both as a beam and whilst partly filled or under sudden suction due to increase of load.

Actually pipes are met with, varying from more than 12 ft. in diameter and some $\frac{3}{8}$ in. thick at low heads, to a diameter of 19 in. and $1\frac{3}{4}$ in. thickness of weldless steel, as in the 5 000-ft. head pipe-line at Lac Fully, in Switzerland.

The water pressure upon the interior of the pipe increases proportionally to the head as the pipe descends from the forebay to the power house. For this reason long pipes are sectionalized, and the material, size, thickness and, occasionally, the number of pipes, are varied so as best to suit the conditions of each particular section.

With regard to the choice of the number of pipes to convey a given quantity of water, the best practice is to make the number as small as possible, often using one only. This may be seen by considering that the total section of the pipes is kept unchanged while the number is varied. The smaller pipes will not need to be so thick, both thickness and diameter being proportional to $\sqrt{(1/n)}$, where n is the number of pipes. The area of metal per pipe is therefore proportional to $1/n$, and the total metal $n \times (1/n)$ is unaltered. At the same time, however, the efficiency of the pipe is decreased, as the frictional loss of head, being roughly proportional to the wetted surface, is increased by using a number of small pipes.

In practice more than one pipe is used, and sometimes as many as five or ten. This is sometimes due to the fact that the installation is made step by step, or to manufacturing, transport, or erection considerations. For pipe lines up to a few hundred feet in length it is a common practice to put one pipe to each turbine, thus giving reliability and avoiding the losses inherent in the distributor pipe which would otherwise be necessary.

Choice of Diameter.

The basic principle upon which all economical design depends is that an additional small investment of capital upon any part or item of the plant should give the same return, and that that return should be equal to the market rate of interest on this investment, plus the annual depreciation on this investment at a percentage suited to the item in question, plus an allowance for profit.

In this case an increase in the diameter of the pipe would result in a definite additional capital outlay. It would result in a gain because the decrease in the frictional loss would render an equal amount of energy saleable, and the gain would be the sale price of this energy. It would also result in a loss because the turbine and the generator would have to be correspondingly larger, working at a slightly higher head because of the decrease in the frictional loss.

The annual value of the energy gained should be just sufficient to pay for the interest, depreciation, and profit charges on the increase in cost of the pipe and the increase in cost of the generating unit. This consideration enables an economic limit to be arrived at.

Water Turbines and Specific Speed.

In practice only two types of water turbines are generally used, the Pelton impulse wheel, best for small powers and high heads, and the Francis reaction turbine, best for large powers and low heads.

The conditions determining which type is the more suitable for a given case are largely summed up in the specific speed, which depends solely upon the geometrical proportions and shape of the wheel, and not upon its size.

If a runner of given geometrical form be placed under a given head there will be only one speed at which the velocity of flow of the water and the velocity of the blade are so related that the water enters without shock and leaves with low velocity, and therefore only this speed will give the best efficiency. The spouting velocity of water at a head H is proportional to $\sqrt{H}$, and, therefore, keeping the turbine always running so that the water enters without shock, the velocity of the blades must be proportional to $\sqrt{H}$ and the speed (r.p.m.) to $\sqrt{H}/D$.

The power developed is the product of the quantity of water and the head, i.e. it is also proportional to $\sqrt{H}D^2H$, since the area of the water passages for geometrically similar wheels is proportional to D^2.

We have then the two proportions:

$$N \propto \frac{\sqrt{H}}{D}$$

and $$P \propto H\sqrt{H}D^2, \text{ or } D \propto \frac{P^{\frac{1}{2}}}{H^{\frac{3}{4}}}$$

Eliminating D, we have

$$N \propto \frac{H^{\frac{5}{4}}}{P^{\frac{1}{2}}}$$

or $$N = K\frac{H^{\frac{5}{4}}}{P^{\frac{1}{2}}}$$

where K is defined as the specific speed.

Pelton wheels have specific speeds of less than 5 or 6. Francis turbines have specific speeds of from 15 to 125. Intermediate values may be obtained by using more than one Pelton wheel mounted on the same shaft, or wheels with more than one jet. Since for a given turbine speed the specific speed must vary as $\sqrt{P}/H^{\frac{5}{4}}$, it will be seen how the head and power determine the choice of type of wheel.

Draught Tube.

The draught tube is an integral part of the turbine, as it is used to recover the energy represented by the head which the water retains when leaving the turbine, and the energy due to the velocity with which it leaves the turbine.

Headworks and Forebay.

The forebay at the head of the pipe line has two main functions:—

(1) To supply water capacity to meet a sudden change of load, as the water in a long canal or flume cannot quickly adjust its flow to new conditions. If no capacity were provided at the forebay a sudden increase of load would drain the forebay, and a sudden decrease of load would cause it to overflow, owing to the inertia of the water running into it.

(2) To remove foreign bodies from the water, the water velocity is reduced so that sand and grit settles, and straining racks (trash racks) are provided, first of coarse and then of fine mesh.

Storage and Regulation of Flow.

There are really two distinct reasons for providing hydro-electric plants with water storage, as follows:—

(1) During any day the mean power which may be generated is proportional to the total flow of water. For most purposes, however, the load curve is peaked, and the flow of water must follow the peaked load curve, and if the whole of the available water is to be used, some of it must be stored at times of low load, so as to be available for times of peak load. This storage is sometimes called "pondage," and is often placed at or near the forebay, so that the works above the forebay may be designed to meet only the mean load, not the peak load.

(2) Storage from wet to dry parts of the year, and from dry to wet years. The whole problem is very similar to that of ordinary town water-supply, but is usually on a larger scale. It is worth noting that storage at the head of a river serves for the seasonal regulation of all water-power stations farther down the river. This is one reason, amongst several, why the water development of a river must be considered as a whole, i.e. as one problem from source to mouth.

Two factors largely decide the desirability of storage, the first being the head at which the plant works. A given quantity of water stores an amount of energy proportional to its head. For example, a 10-ft. cube of water at a head of 5 000 feet represents about 120 kWh, but at a head of 20 feet represents only about 0·5 kWh. For this reason high-head plants are provided with storage wherever the ground permits, but low-head plants never have storage.

The second factor is the frequency with which the reservoir is filled and emptied. Clearly, the mean power from a given storage is proportional to this. This is the reason why daily pondage presents so few problems, as compared with seasonal storage. It is also the reason why storage from dry to wet years is practically never found, and why a district with two wet seasons favours storage more than does a district with only one.

Storage for Tidal-power Regulation.

These two principles have an interesting application in schemes for developing tidal power, where the problem

of fitting a peaked power-supply curve, with its peaks at variable hours of the day, to a peaked but stationary demand curve is probably not capable of a very cheap and easy solution. It has been suggested that a high-head storage reservoir should be established near the tidal power station. At times of excess power it would be used to pump water up to the reservoir. This water would be run out to supplement the tidal power when required, special high-head turbines being provided.

This regulation by pumpage is not untried; there is a small river station at Walker Burn on the Tweed so regulated with a 1 000-ft. head reservoir, and a larger one at Vouvry in Switzerland working at 3 000 ft.

There are three separate frequencies to be considered in the case of tidal power:—

(1) The tidal power, utilized on rise and fall, has a peak every 6 hrs. $12\frac{1}{2}$ mins.
(2) The load curve has a peak every 24 hours.
(3) The tidal power available is four times as large at spring tides as at neap tides, with peaks every fortnight. If the actual cost of the high-head reservoir were very large, as seems likely to be the case, it might be profitable to store for the high-frequency variations, but not for the low-frequency variations, i.e. it might be more economical to turn the tidal power into constant available power without providing storage to distribute this power over a commercial load curve with a correspondingly higher peak value, and similarly it might be profitable to develop fully the neap tide power and neglect the excess at spring tides.

Interconnection and Storage.

When power plants are fed by streams having a different variation of flow with the seasons, as when one is fed by melting snow and the other by rainfall, they may be electrically interconnected, and the seasonal storage required is thus reduced. Similarly, on tidal-power development schemes it has been suggested that the power from estuaries having different tidal times, when fed into a common network, might be arranged to avoid or diminish storage. Such schemes have been proposed for the Severn and the Dee; and for the Forth, Clyde, and Solway Firth.

Tidal Power.

When the tide rises, work is done in lifting an immense mass of water against gravity. The rate at which work is done, i.e. the power, is enormous. It has been estimated, for instance, that the Irish Sea absorbs at times anything up to 6 000 million kW. In the open oceans the greater part of this energy is restored on the fall of tide, the tidal heap or wave simply swinging round the earth. Shallow seas and narrow places absorb a large quantity of tidal energy in friction, which is supplied by a corresponding decrease in the rotational energy and speed of the earth. Since this energy of rotation is sufficient to supply 1 000 million continuous kW for 800 million years, neither the immense tidal losses nor such trivial additions to them as any human harnessing of the tides might make, will cause any perceptible lengthening of the days and nights during any period of immediate interest to us.

During the past few years there have been a number of schemes for turning the tidal power to account. These are of two main types. The first consists of a float or floats rising and falling with the tide, and coupled by cranks, for instance, to apparatus on shore. This scheme cannot be expressed correctly in figures, for if we take a float of 1 000 tons' displacement on a 20-ft. tidal range, the power would be only 1·4 kW, as follows:

Energy every 12 hours $= 20 \times 1\,000 \times 2\,240 = 4{\cdot}48 \times 10^7$ ft.-lb.

$$\text{Power} = \frac{4{\cdot}48 \times 10^7}{12 \times 60 \times 44\,000} = 1{\cdot}4\ \text{kW}$$

The more hopeful type of solution is that in which a large estuary is dammed, the dam being fitted with sluice gates and containing turbines more or less as in a low-head river development. The reservoir so formed is filled at high tide and the water is retained behind the dam as the tide falls outside. When it has fallen so that sufficient difference of level has been established, water is allowed to flow out through the turbines in the dam, generating power. Alternatively, the method of working may be to lock the rising tide out while the reservoir remains empty, and the power is developed while water is allowed to flow in and fill the reservoir. Finally, if obvious practical difficulties can be overcome, it should be possible to combine the two and obtain power from the same turbines both on the inflow and on the outflow of the tide.

This power supply is intermittent, for, in order to obtain a working head, the reservoir cannot begin to empty until some time after it has been filled at high tide, and it must be quite empty before the tide rises again. Since the tidal period is 12 hours 25 minutes, the working periods become later each day and cannot be made to fit any load which occurs at the same hours each day. This problem is the one upon the solution of which the economical development of tidal power waits, namely, either to adapt or create industrial processes which will utilize power as and when it is available, or alternatively, to find a means of storing energy in order to fit the irregular supply to the variable demand of industrial load.

A further solution is to use an additional low-level tidal basin, or sump, into which water may be run either from the high tide or the high water in the main reservoir, at such times as power would not otherwise be available.

Power from a Basin.

On a 20-ft. tidal range one square mile of reservoir area may be readily shown to represent energy equivalent to 132 000 kWh, i.e. it would lose this potential energy if it were discharged at low-water level. With the power developed on both inflow and outflow this would give a mean continuous output (at 100 per cent overall efficiency) of 22 000 kW per square mile.

The power available is proportional to the square of the tidal range. Some estuaries, e.g. the Severn, have neap tides of 20 feet and spring tides of 40 feet. The mean power is therefore at least double that given above for a range of 20 feet, and for 20 square miles of basin area would give (at 60 per cent overall efficiency) over 500 000 kW continuous power, or the equivalent of 1 000 000 kW peak capacity on an industrial load factor of 50 per cent. The Severn tidal-power scheme is of this order of magnitude, and at least as much power again is available around our coasts and is possibly on the margin of being commercially remunerative.

Competition and Co-operation of Steam and Water-power Stations.

All other considerations apart, under a commercial system one absolute limit to the development of water power is the condition that it shall not be more commercially profitable to supply the same power at the same place by fuel-power stations. It is also true, however, that a combination of water and steam plants, electrically interconnected, is very often the cheapest way to meet a given power demand, even when abundant water power exists to meet it unaided. The economic solution depends upon the load factor of the load it is intended to supply, or upon the charges which energy at various load factors will bear. For example, a very high load factor may be obtained by developing electrochemical industries, but the cost per unit which will render this development remunerative is rigidly limited by the cost of alternative methods of production.

The costs of generating energy by any means may be divided into a cost specific to each unit and an overhead cost independent of the number of units generated, but depending mainly on the peak capacity. With a higher load factor the fixed charges are spread over a larger number of saleable units, and the cost per unit is decreased. If the fixed charges are large compared with the generating charges, a high load factor will have more effect in reducing the cost per unit than if the reverse is the case.

In hydro-electric installations there are many cases in which practically the whole costs are the fixed charges, i.e. interest on capital, rents, etc., and in such cases a high load factor is necessary if the cost per unit is to be small, and an installation which could not compete with steam at ordinary load factors might be a sound proposition if required to supply a specially high load factor.

In hydro-electric schemes involving expensive seasonal storage the reverse is the case. The amount of storage capacity required is fixed by the mean daily load, not the peak load, and hence the greater part of the reservoir cost is a cost proportional to the energy developed, i.e. to the load factor. In fact, the water has now a cost, just as fuel in a steam station has a cost, and the storage development is under exactly the same economic forces as a station using expensive fuel for every unit it develops. In this case the load factor of the station is of correspondingly small account, and it may be that such a station which could not compete with steam to supply continuous power could compete with it successfully under industrial load factors, though this would be an extreme case.

It will now be seen why a compound station may be the most economical proposition to meet a given load. It will be possible to keep part of the plant running constantly, part running, say, for 50 per cent of the time, part running for only the brief period of the peak loads, and part, the standby units, running only in cases of emergency. According to circumstances, water-power units will meet some of these demands best, and steam units will meet others best, and the station will be made compound.

In low-head developments without storage, i.e. where the water is either used or wasted, the steam units are therefore used to take the peak loads, and the water units are set to run constantly at their most efficient output, using all the water which is available up to their maximum capacity.

In high-head developments with seasonal storage it is sometimes better to run these steam stations at constant load and to take the peaks on the water, for the reason explained above.

Where high- and low-head developments are connected into a comprehensive system, as in Switzerland, it is the practice to run the low-head developments at constant power and take the peak loads from the storage stations.

In England, where there is considerable possibility of developing a large number of low-head stations of small power connected into the steam supply network, it would be possible to run these at continuous full load, and, though the load factor of the steam stations would be so much the worse, it is clear that this possibility renders the limit of cost per kilowatt which would make such a development possible, rather higher than it would otherwise be.

Cost of Water-power Development.

There is a definite limit of capital cost which cannot be exceeded by a water-power development. This limit depends upon the distribution of the load through the day and upon the charge per unit which the prospective consuming process will bear, and cannot, therefore, be stated at a definite figure. It also depends upon the location of the water power.

It has been shown in the report of the Water Power Resources Committee that a liberal allowance for medium-sized plants for all the annual charges whatsoever is 11 per cent of the total initial outlay.

If the limiting expenditure for development is fixed solely by competition with coal-fired stations, the limiting cost per kilowatt may easily be estimated from the equation :—

11 per cent of this expenditure
= annual cost of the equivalent steam station.

On a pre-war basis a 5 000-kW steam-power station with coal at 10s. per ton, and with an annual load factor of 95 per cent, would cost about £37 000 per annum. This is 11 per cent of the allowable cost (pre-war) of a 5 000-kW water-power station, which makes its limiting cost per kilowatt £67 for the same duty. If the average value of money is, as at present,

half its pre-war value, the present economic limit is twice as much, or £134 per kilowatt. At lower load factors the limit would be lower, probably about £45, i.e. the pre-war cost at 50 per cent load factor.

The cost per kilowatt of actual installations is very variable. A 10 000-h.p. station at Chedde in France cost only £7 per kilowatt. The average (pre-war) cost per kilowatt of the installations in various countries are as follows:—

	£
Canada (70 typical larger plants) ..	17·7
Canada and U.S.A (average) ..	25·0
Scotland	33·0
Sweden..	15·0

British Water-power Resources.

The extent and availability of the water-power resources of the British Isles have just begun to attract the attention of engineers. The report of the Water Power Resources Committee of the Board of Trade has just been issued, and, although only selected districts were investigated by the Committee, they consider that in those districts there is power of 210 000 kW (continuous) in Great Britain capable of economic development and more than 200 000 kW (continuous) in Ireland. In Great Britain this represents 40 per cent of the total units generated for public supply, railways and tramways in 1917–18. In Ireland the amount is, of course, vastly more than the whole so generated. This leaves out much water power not investigated, particularly the low-head river sites in England. An investigation of a typical river, the Wiltshire Avon, showed 4·4 kW per square mile of catchment. The area of England is 50 000 square miles, and although this is very little data, it indicates that there are considerable resources not included in the Committee's estimate; and there is also a total of at least 1 000 000 kW (continuous) of tidal power not far from the limit of economic availability.

Water-power Developments Abroad.

Almost every country has made rapid progress in the past 10 years in investigating and developing its water-power resources. Everywhere plans are made for huge developments which only await economic prosperity to be put in hand.

General Economic Effects.

The steady development of resources of this magnitude constitutes perhaps the most important engineering movement at present occurring. The causes for it are the technical advances in turbine and electrical engineering, the spread of the industrial point of view all over the world, and the effects of the war upon the supply of coal and of manufactured goods.

Probably about one-fifth of the total mechanical prime-mover power of the world is water power as at present in operation. It is certain that this fraction will be much increased in a few years' time. The available water power of the world is vastly greater than its power consumption, but its development will proceed slowly because it is very often situated away from industrial areas. It is certain, however, that in the long run the load will go to the power, and transport, which is one of the difficulties of development, will be provided where it is required.

This development has a double interest for this country. First, it is creating a demand for civil engineering plant. electrical generating plant, high-tension transmission and control gear, industrial equipment, etc., which British engineers have to study. This demand can be met in the first place only by established industrial countries. It is also developing a market for trained industrial skill.

The ultimate effect of this movement towards universal industrial development, of which water-power development is one important aspect, may be less fortunate for the people of this country. We have held, together with a few other countries, a monopoly position as universal providers of manufactured goods. In so far as it does not depend upon new demands and increased consumption, the development of industry in new places must of necessity restrict the markets of the established countries. The process has not yet become important, but it seems probable that it will underlie the industrial history of the years when we shall be most interested in such movements.

THE EFFECT OF LOCAL CONDITIONS ON RADIO DIRECTION-FINDING INSTALLATIONS.

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SUMMARY.

This paper is an account of some of the experiments carried out during the past year by the Sub-Committee of the Radio Research Board on Wireless Direction Finding.

The majority of the work was done either at the Radio Research Station, Slough, or the National Physical Laboratory, Teddington.

The paper summarizes the work of previous investigators on the same lines, and indicates why further reasearch was necessary. It then describes experiments which provide quantitative data as regards the effect of metal work, coils, aerials, overhead wires and trees on a direction-finding set in their vicinity, and gives definite figures which show the extent in certain cases of errors produced by mountains and buildings.

INTRODUCTION.

Modern direction-finding installations are well able to detect variations of less than 0·5° in the direction of arrival of the waves under observation. There are, however, many causes which may prevent the readings so obtained from corresponding to the absolute direction of the transmitting station observed to this degree of accuracy.

An analysis of the various classes of errors experienced in practice shows that by far the most important are those which have been somewhat vaguely termed "night effect," implying the variation in the apparent direction of arrival at the direction-finding station, a phenomenon which is observed with nearly all transmitting stations between sunset and sunrise. These variations commonly amount to 20° and have been observed by the authors to exceed 40° on certain occasions. Little is known, however, as to the cause producing these effects, though much has been surmised. No practical system has been put forward which avoids these errors, and there is, at present, little more to be said about them save that, by reason of their existence, radio direction-finding is practically restricted to the daytime except over very short distances.

Second in importance is the class of error dealt with in this paper, namely, the errors which are produced by the immediate surroundings of the installation.

Effects of this kind may be caused by neighbouring objects, or by local geographical conditions, and while the errors produced will be constant under ordinary circumstances and thus permit of correction of the bearings, in other cases it may be necessary to avoid all possible errors at the site of the installation. It was known previously that such objects as cliffs, hills and mountains, trees, masses of metal work, and overhead lines would produce very serious errors on a direction finder operated in the vicinity, while the special case of the effect of the metal hull of a ship has seriously engaged the attention of wireless engineers ever since the first ship was fitted with directional apparatus.

Round * has indicated these facts in a general way, while Ballantine,† in an account of some researches of the U.S. Navy Department, gives some interesting details of local errors met with in special cases. Hollingworth and Hoyle have also given the results of experiments conducted in this matter,‡ while more recently Kolster and Dunmore have mentioned some of the errors experienced in towns and on board ship.§

Notwithstanding the above work, however, there is insufficient data on the matter indicating exactly what errors are produced, their probable magnitude and at what distance from the disturbing objects the receiver must be placed in order to render such errors negligibly small.

A knowledge of these facts is particularly important in selecting a suitable site for the erection of a directional radio installation. It is the experience of the authors that it is very difficult to obtain for direction finding an absolutely ideal site, which is not prohibitive for other reasons, particularly in the vicinity of towns. It has, for instance, been found desirable to have some idea as to which of several conditions will produce the least serious effect, and at approximately what spot the observed errors will be a minimum.

The experiments described in this paper were therefore carried out in order to obtain some quantitative knowledge of the disturbing effects of surrounding objects on a directional receiving set. Unless it is otherwise stated, the experiments were conducted with a direction finder of the Robinson or crossed-coil type,‖ which was transported to and from the scene of operations as required. In a few cases, however, a smaller single-frame coil was used for convenience, and due mention will be made of this at the correct place. The orientation of the coil for each experiment was carefully carried out by means of a good prismatic compass, which could be relied upon to within ½ degree.

* H. J. ROUND: "Direction and Position Finding," *Journal I.E.E.*, 1920, vol. 58, p. 224.

† S. BALLANTINE: "The Radio Compass," *Wireless Year Book*, 1921, p. 1131.

‡ J. HOLLINGWORTH and B. HOYLE: "Local Errors in Radio Direction Finding," *Radio Review*, 1920, vol. 1, p. 644.

§ F. A. KOLSTER and F. W. DUNMORE: "The Radio Direction Finder and its application to Navigation," *Scientific Papers of the Bureau of Standards*, No. 428, 1922.

‖ J. ROBINSON: "A Method of Direction Finding of Wireless Waves, and its Applications to Aerial and Marine Navigation," *Radio Review*, 1920, vol. 1, pp. 213 and 265.

The various obstacles and features of the surroundings which are dealt with from the point of view of their disturbing effect are classified as follows:—

(1) Metal work in small and large quantities above and below the ground.
(2) Overhead wires (e.g. telegraph and telephone wires or power lines).
(3) Tuned aerial systems and closed coils.
(4) Trees.
(5) Buildings.

(1) METAL WORK IN SMALL AND LARGE QUANTITIES.

(a) *Small metal work.*—The presence of metal work near a receiving set would be expected to have some effect upon the working of the latter, owing to the currents induced in the metal by the arriving waves and to the inductive action of these currents on the receiving coil itself. Unless the metal work is arranged in the form of a closed loop near or around the circuit, the influence of such currents set up in stray metal work would not be felt at any appreciable distance from the metal object. It is easily shown experimentally that the presence of pieces of metal smaller than the dimensions of the coil system do not give rise to perceptible errors in the readings of the latter except when placed very close to the coil. It was found that various metal boxes used in connection with the screening of an auxiliary triode oscillator did not make any difference in the observed bearings when placed 5 or 6 ft. from the coil. Similarly, the screening box used for the amplifiers and batteries of the direction finder gives no noticeable errors when at a distance of 6 ft. from the centre of the coil system.

This latter box, which was constructed of sheet iron and the dimensions of which were 20 in. × 20 in. × 30 in., was found to produce an error in the bearing of Paris at Teddington of about 1·5° when placed at about 3 ft. from the coil's axis. The error was found to be greater when placed to one side of the coil perpendicular to the direction of Paris than when placed approximately in a line with Paris and behind the coil. By moving the box to the other side of the coil the apparent bearing was changed in the reverse direction. In these positions the box lies within 6 inches of the vertical sides of the large coil at certain settings, and the currents in the coil then probably induce other eddy currents in the metal, which will give additional effects in the former. By removing the metal box to a distance of 5 ft. the resulting error becomes inappreciable. When the box is placed inside the crossed-coil system the effect of the eddy currents is most marked, resulting in a large reduction of signal strength in the receiver.

The general conclusions thus arrived at are, therefore, that masses of metal work comparable in dimensions with the receiving coil do not perceptibly produce any errors in the bearings indicated by the latter except when placed within a very few feet of the coils. As a safe precaution it is as well to keep the space of, say, 10 ft. round the coil fairly clear of even small pieces of metal, as the cumulative effect of several small pieces may become quite appreciable. For this reason it is advisable to ensure that the hut or other structure containing the direction-finding set is as free as possible from metal in the way of joint-plates, door and window fastenings, etc., and that metal oil stoves or lamps are not placed too close to the receiving coils.

(b) *Long metal tube.*—When, however, the extent of the metal work in the neighbourhood is moderately great, the resulting errors in observed bearings become very much more serious. As an illustration of the order of the errors which may arise in such cases, the results of an investigation carried out on a large metallic tubular construction may be given. The "tube" was of approximately semi-circular cross-section, being formed of a number of curved, corrugated iron sheets bolted together and resting on flat, similar sheets placed on the ground. The tunnel so formed was 50 ft. long, and the height of the arch about 3 ft. 6 in.

The alteration, due to the tube, of the electromagnetic fields set up by waves arriving from various transmitting stations was then explored by means of a single receiving coil 2 ft. 6 in. square mounted on an axis in a horizontal base-board with scale and pointer. This coil, provided with tuning condensers and an amplifier and batteries, formed a very small, portable direction-finding set operating on the simple "minimum" principle, which could be used inside or outside the above tube. In each position in which the coil was used, the latter was set by means of a good prismatic compass to read either 90° or 270° when the plane of the coil was in the geographical meridian. When the coil was then turned to the minimum position for any received signals, the pointer indicated directly the bearing of the station observed. This setting of the coil could be made to about 0·25°, and a few check-experiments carried out with the coil set up in an open field well away from all obstacles showed that it gave correct bearings, as indicated by the "standard" direction-finding set in use at the station. This latter set was used as a frequent check throughout the experiments, to ascertain the changes produced by the alteration in position of the smaller coil. The average accuracy of

TABLE 1.

Relation between the Change in Apparent Bearing produced at the Centre of the Tube, and the True Direction of the Waves relative to the Tube's Axis.

Transmitting station	Directions relative to axis of tube	Change in apparent bearing
	degrees	degrees
Nauen	2	12
Budapest	27	32
Paris	69	14
Aranjuez	115	16
Horsea	131	26
Poldhu	169	14
Cleethorpes	292	15
Karlsborg	323	29
Moscow	348	16

the readings obtained on the latter was about 0·5°, which was considered quite sufficient for the purpose required.

The influence of the metal tube first became appreciable when the coil receiver was placed about 30 ft. from either end of the tube and on its axis, when an error of bearing of about 1° was produced. When placed at the open end of the tube, this error increased to 2°–5° for various transmitting stations. As the coil was then moved down the axis inside the tube, the error increased rapidly to a maximum value over a distance of about 15 ft. on either side of the centre of the tube, this maximum error varying with the direction of the arriving waves relative to the tube's axis and becoming as great as 29° in one case. Table 1 summarizes the mean values of several readings taken on the different transmitting stations, and also shows the directions of these relative to the tube.

have by far the greatest effects. For example, with the above coil receiver placed inside the tube near the centre, the removal of a section of the tube, 2 ft. 6 in. long, forming the top sides reduced the error in the apparent bearing of Paris from 14° to 1°. Similarly, by unbolting two adjacent sections and slightly separating them, a change of 2° or 3° was produced.

With the receiving coil set up along the outsides of the tube, the errors observed were very much less than those recorded above, ranging from 5° to 9° at a distance of 2 ft., to about 2° at 3 ft. from the side of the tube. Also, when the coil was placed on top of the tube the errors varied from 2° to 6°.

(*c*) *The case of a ship*.—As a further example of the effect of large masses of metal work upon the readings of a directional receiver, the effect of the metal hull of a ship may be instanced. In June 1921 one of the authors installed a standard Robinson direction-finding set on one of H.M. surveying ships, with the kind permission of the Hydrographer to the Admiralty, who has shown great interest in the experiments. The particular ship chosen is normally working in the North Sea some 30 to 50 miles out from the coast. The set was installed on the upper deck of the ship and the frame was set as accurately as possible on the centre line, with the scale of the coil reading 0° to 180°. Any observed reading on the direction-finding set was thus made relative to the head of the ship. The direction of the ship was obtained from the standard compass and, after correcting for compass error and magnetic variation, the apparent wireless bearing of the distant transmitting stations could be obtained. A large number of observations on various transmitting stations were taken in this manner.

The earlier experiments soon showed that the metal work of the ship had a considerable effect on the

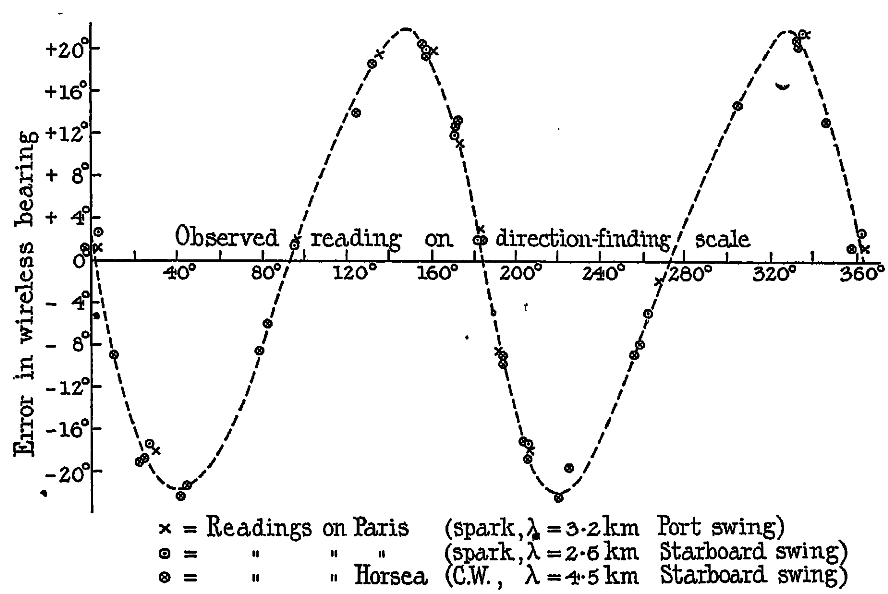


FIG. 1 (*a*).—Observations of bearings made on H.M.S. "Fitzroy" during swinging of ship, 17th October, 1921.

In each case the change in the apparent bearing was towards the normal to the tube's axis, showing that the magnetic field resulting from the incoming waves is deflected in a direction towards the axis of the tube. Table 1 shows that the deflection produced is of the nature of a quadrantal error. Immediately the coil was placed inside the tube a very marked decrease in signal strength was observed, which is evidently due to the eddy-current losses resulting from the currents set up in the metal work by the incoming waves. The greatly increased effect of metal work when placed in the form of a partly or completely closed loop is well demonstrated by the above results, and illustrates the effect which might be expected if, for example, a directional wireless receiver were installed in a corrugated-iron building. The continuity of the metal structure would appear to be very important, and even with such large masses the nearest portions of these

observed readings of the direction finder. It was therefore arranged to "calibrate" the ship by gradually swinging to various points of the compass, and taking sets of observed bearings on the same transmitting station.

The stations observed during the successive swings were Paris (3·2 km wave), Paris (2·6 km wave), and Horsea (4·5 km wave), and the results are shown in Fig. 1 (*a*) plotted in the form of error of bearing against reading on the direction finder. In Fig. 1 (*b*) the same results have been plotted to show the deviations against the actual direction of the incoming waves relative to the ship.

In consideration of the conditions under which the observations were made, the results are seen to lie fairly accurately on the mean curves plotted, and the latter demonstrates well the following points:—

(i) That when the arriving waves come from either approximately fore and aft or athwartships, the error in the reading is reduced to zero.

sinusoidal. The departure of the curve in Fig. 1 (*b* from sine-wave form may easily be due to the departure of the general shape of a ship from the above ideal form.

It would be expected from these theoretical considerations that a directional receiving set mounted symmetrically over a metal ship would have a zero error for readings of 0°, 90°, 180°, etc., whereas the above curve is displaced some 5° or 6° from these positions. As the setting of the coil on the ship was considered to be correct to within 1°, this difference may be due to some asymmetry in the distribution of the metal work on the ship, particularly on the deck.

The above results show, therefore, that when the mass of metal work is very large compared with the receiving coils, as in the case of a ship, the resulting errors in the observed bearings on the direction finder may be very serious; although, when the set is fixed in position on the ship, the necessary correction may be made from such a curve as that given in Fig. 1 (*a*).

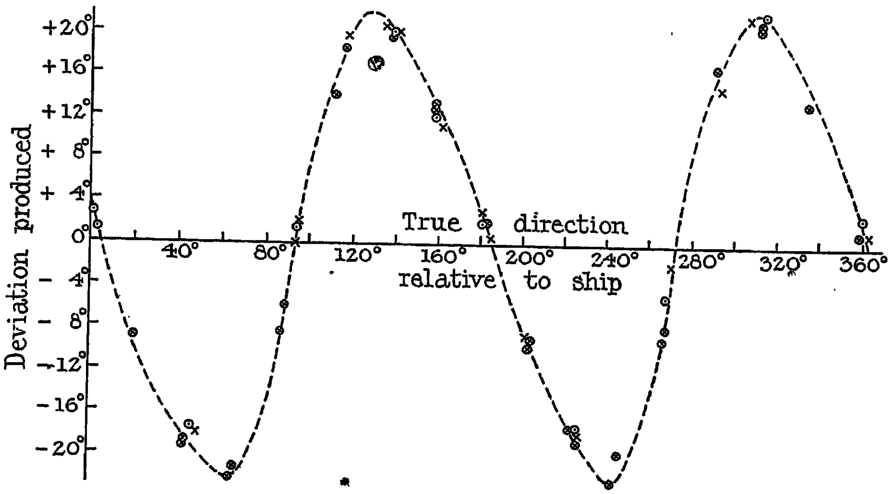


FIG. 1 (*b*).—Observations of bearings made on H.M.S. "Fitzroy" during swinging of ship, 17th October, 1921; plotted to show the deviation produced on waves arriving at various angles to the ship.

(ii) That in intermediate directions the results are in error by amounts varying up to 22° in either direction.

(iii) That there is a tendency for the readings to be concentrated along the fore-and-aft line of the ship.

(iv) That there is no appreciable difference in the error incurred on the different wave-lengths used, viz. 2·6, 3·2 and 4·5 km.

Conclusions (i), (ii) and (iii) above are in direct accordance with the experience of previous investigators. Further experiments on other transmitting stations have confirmed conclusion (iv) over the range of 2·6 to 6·0 km.

The theoretical treatment of the deviations of electromagnetic waves due to a metal cylinder half immersed in sea water has been given by R. Mesny,* who shows that the deviation curve for such a case should be

* R. MESNY: "The Diffraction of the Field by a Cylinder, and its Effect on Directive Reception on Board a Ship," *Radio Review*, 1920, vol. 1, pp. 532 and 591.

(*d*) *Underground metal work.*—The effect of masses of metal work in producing large errors in the reading of a radio direction finder may in some instances be utilized for the location of such metal work, when the latter is not visible or when its presence is not readily detected by other means. An interesting example of this was recently obtained at the Aberdeen University direction-finding station of the Radio Research Board. This station was erected on a site which appeared to be fairly good as far as conditions above ground-level were concerned, but when it was operated some large errors were soon found in the apparent directions of the incoming waves. These errors were found to be practically permanent in the daytime, and Fig. 1 (*c*) shows graphically the mean day errors experienced in the daytime between June 1921 and April 1922. From a comparison of this and the previous curves it will readily be seen that one possible cause of such a curve of errors would be the existence of a mass of metal work the greater axis of which is in the direction 163°

from true North, and passing directly beneath the direction finder.

By means of a portable directional receiving set the authors explored the site and found that the errors were closely associated with a line of manholes indicating the location of a sewer crossing the adjacent fields at an angle of 170° from true North. The hut containing the standard direction-finding set was inadvertently erected almost directly above this sewer at a point where the latter rose to within 18 in. of the surface. The sewer was of ordinary brick and concrete construction and contained no metal work except at the manholes, and it seemed unlikely that this could be responsible for the effects observed. An inspection of the necessary plans, however, showed that the part of the sewer in the immediate locality of the direction-finding hut was a section of special construction, owing to its proximity to the surface, was supported by a strip of expanded steel 6 ft. wide and 300 ft. long, and was 8 ft. below the surface at the hut. In addition to this, the sewer crossed a small stream at a point about 14 ft. from the hut, and the stream was conducted under the sewer by means of an iron pipe about 40 ft. long. The existence of this metal work entirely beneath the surface may therefore be considered to have been predicted from the readings obtained on the radio direction finder. It is to be expected that other large masses of buried metal work, such as gas and water mains, will have a similar effect in their vicinity.

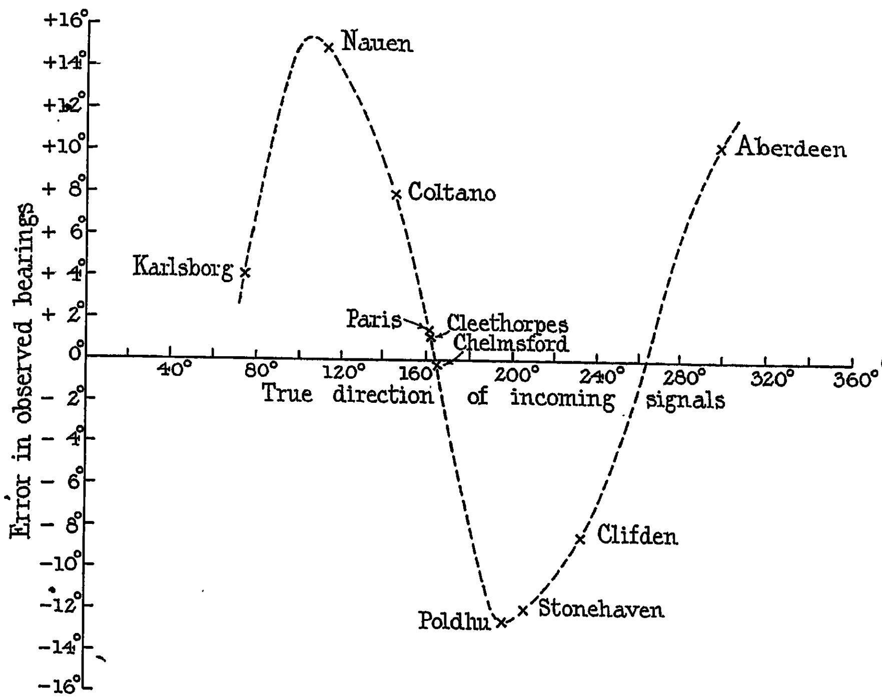


FIG. 1 (c).—Curve showing permanent deviations in bearings at Aberdeen University direction-finding station. Mean day error observed from June 1921 to April 1922.

(2) OVERHEAD WIRES.

A possible cause of errors which is frequently encountered in selecting a site for a direction-finding set, is the presence of overhead conducting wires. From the conclusions arrived at in Section (1), it might be considered that a bunch of such wires, being of comparatively small bulk, would produce only small errors, and these only at distances of a very few feet from the wires. The experiments about to be described, however, show that when the wires extend for a considerable distance the effects produced in their neighbourhood can be very large indeed.

It should here be emphasized that, in any attempt to study the effect of a local condition on a directional radio installation, every precaution must be taken that other conditions are either ineffective or else remain constant throughout the experiments. The fulfilment of this provision was found to be somewhat difficult in the present case, where a convenient situation of overhead telegraph wires was required quite free from hills, trees, wire fences, etc., which might produce other effects quite extraneous to those sought after.

One fairly satisfactory site was, however, found near the Slough station, and a number of experiments were carried out with the small frame coil mentioned in Section (1) in connection with the metal tube experiments. The site selected was on the main Bath-road about 1 mile east of Slough, along which are installed a large number of overhead trunk telephone wires connecting London with the West of England. About 40 wires were carried on poles along each side of the road, the lowest wires being about 20 ft. above the road. With the exception of a hedge along either side of the road, the surrounding land was quite free from obstacles, and a point was chosen at which a track led off to the South, approximately at right-angles to the road,

and along which the experiments could be carried out.

The frame coil was first set up immediately underneath the wires along the south side of the road and correctly oriented in the geographical meridian. Readings of the apparent bearings of various transmitting stations were then taken in the usual manner. It was at once noticed that the readings obtained were considerably different from the correct values, and it was also noticed that the bearings changed considerably from time to time during the tests. For example,

TABLE 2.

Change in Apparent Bearings due to Two Sets of Overhead Wires (38 and 46 in number), laid in the Direction 127·5° from True North.

Distance from plane of wires	Station observed	Wave-length	Mean observed bearing	True bearing	Error due to wires
ft.		km	degrees	degrees	degrees
0	Paris	2·6	(1) 272·3	143·9	+ 128·4
			92·3		− 51·6
0	Paris	2·6	(2) 249·0	143·9	+ 105·1
			69·0		− 74·9
30	Paris	2·6	159·3	143·9	+ 15·4
60	Paris	2·6	150·8	143·9	+ 6·9
90	Paris	2·6	147·8	143·9	+ 3·9
120	Paris	2·6	146·3	143.9	+ 2·4
0	Paris	3·2	171·6	143·9	+ 27·7
90	Paris	3·2	145·9	143·9	+ 2·0
120	Paris	3·2	145·5	143·9	+ 1·4
0	Nauen	3·9	85·5	77·7	− 12·2
90	Nauen	3·9	74·8	77·7	− 2·9
120	Nauen	3·9	73·5	77·7	− 4·2
0	Chelmsford	3·8	(1) 41·0	70·9	− 29·9
0	Chelmsford	3·8	(2) 35·0	70·9	− 35·9
60	Chelmsford	3·8	63·5	70·9	− 6·0
120	Chelmsford	3·8	65·0	70·9	− 5·9
0	Coltano	4·2	115·0	132·5	− 17·5

the apparent bearing of Paris, after remaining in the region of 90° for about 10 minutes, suddenly changed to about 65°, returning a few minutes afterwards to 85°, the true bearing of Paris being 143·9°. These effects were confirmed by similar tests made several days afterwards, when the bearings reached as low as 45°. Similarly, Chelmsford's bearing during the experiments varied from 35° to 42°. A possible cause of these rapid changes is the alteration of circuit conditions on the telephone wires at the various exchanges to which they are connected.

Having observed the effect of the wires immediately beneath them, the receiving set was then moved away from the road in steps of 30 ft., and the apparent bearings of the various stations were taken at each stage. A summary of the results obtained is given in Table 2, each observed bearing being the mean of several readings taken during the experiments. All readings were taken in duplicate, with the coil in the normal and reverse positions to compensate for any antenna effect in the system which was, however, only of the order of 1°. The readings denoted by (1) and (2) were taken on different days in the same position.

These results show that errors ranging from 12° to 70° may be produced on a direction-finding coil mounted immediately underneath telephone wires some 20 ft. high. The errors produced diminish rapidly as the coil is moved away from the wires, but, even at the distance of 120 ft. from the line of wires, the errors may be a few degrees. At this distance of 120 ft. the effect of the wires on the bearings of Paris was practically negligible, as the error of 1·4° recorded above is exactly the same as that experienced on the standard set at the Slough station, about 1 mile away from the site of the present experiments. As the latter set is mounted in what is considered a nearly "ideal" site, this error must be due to some extraneous cause. The increase in the error on Nauen, when the coil is moved from 90 ft. to 120 ft. from the wires, also suggests the operation of some cause other than overhead wires; possibly the neighbouring trees, although there were only one or two of these within a radius of 100 yards or so.

The explanation of the above effects must remain very obscure, since it is impossible to realize the conformation of the circuits of the telephone lines at any

TABLE 3.

Change in Apparent Bearings immediately beneath the Wires.

Station observed	True bearing of station relative to wires	Deviation of observed bearing
	degrees	degrees
Coltano	5·0	− 17·5
Paris (2·6 km)	16·4	− 51·6
Paris (3·2 km)	16·4	+ 27·7
Chelmsford..	303·4	− 29·9
Nauen	310·2	− 12·2

particular instant. In one sense the overhead wires may be pictured as constituting the top side of a huge vertical frame, of which the earth forms the lower side, and the vertical sides are formed by the connections to earth at the various exchanges. An electromagnetic wave arriving at an angle to the plane of this large frame would suffer a partial absorption of that component of its magnetic field perpendicular to this plane, and the resultant field would therefore affect a direction-finder coil by giving an apparent direction deflected towards the normal to the plane of the wires. In Table 3 the results obtained immediately underneath the wires are collected, and the true direction of the station is given relative to the wires.

Shown in this manner it is seen that, in the case of Paris (3·2 km), Chelmsford and Nauen, the apparent

direction is deflected towards the normal to the plane of the wires. Paris, on the 2·6 km wave, showed some freak effects in the experiments and was evidently subject to some other influence, possibly a resonance condition in the overhead line circuits. At points away from the wires, as shown in Table 3, it exhibits effects similar to those obtained with the 3·2 km wave, and is thus in accordance with the above reasoning. The waves from Coltano arrive nearly along the direction of the wires, and are apparently deflected in the wrong direction. It should be remembered, however, that the overhead wires are not straight over any appreciable portion of their route, and, in fact, suffer a large deviation within ½ mile on both sides of the site of the experiments described. The "effective" plane of the wires may therefore be several degrees different from their direction at any particular point, and this may easily account for such discrepancies as that presented by Coltano.

Some later experiments were carried out under a line of 12 wires, branching off the above main route, at about the centre of their run of less than ½ mile. In this case deviations of bearings ranging from 8° to 31·4° on a few stations were observed underneath the wires, these errors decreasing to from 1° to 6·4° at a point 60 ft. away. It would thus appear that the errors produced are not directly influenced by the actual number of wires near the site, but depend on the conditions of a whole circuit of wires, which may extend over several miles.

It is thus seen that the presence of overhead metal wires in the neighbourhood of a directional wireless receiver may produce very serious errors on the latter, even at a distance of 100 or 200 ft.

(3) Tuned Aerial Systems and Closed Coils.

A comparatively short overhead wire system such as that of an ordinary "open" radio-telegraphic aerial would naturally be considered to have a much greater influence on the readings of a direction finder when it is tuned to the incoming waves. In this case the possibility of an additional field due to re-radiation or induction from the aerial is not remote. A. H. Taylor drew attention to this possibility in some experiments which showed that the tuning-in of a neighbouring aerial some 20 ft. away produced no effect on the direction-finder coils unless the aerial lead was brought to within 8 inches of the latter, when a change of 3·8° in the apparent bearing was produced.*

An instance of a much greater effect than this is also quoted by Hollingworth and Hoyle,† in which the tuning-in of an aerial ½ mile away produced an error of about 4°, but only when the aerial was almost exactly on the line joining the transmitter and the direction finder.

At the spot chosen for the erection of the direction-finding set at the National Physical Laboratory, two single-wire aerials were originally suspended from a mast some 300 ft. away from the set (see Fig. 2). The nearer of these aerials, however, passed within about 40 ft. of the coils at the nearest point of its length of 350 ft. One of the aerials was constantly tuned to the short wave-length of Paris (2·6 km) for the reception of time signals, while the other and nearer aerial was usually directly connected to earth. It was shown by the daily observations made on the direction-finding set that the mere existence of these aerials, proved by their subsequent removal, made no appreciable difference in the observed bearings.

Before their removal, however, the opportunity was taken of making a few experiments on the effect of tuning the aerials. The experiments were made by setting one observer to take readings of the apparent bearing of the transmitting station at regular intervals of 1 minute, while the aerial was alternately tuned to the incoming waves and then connected to earth at intervals without the knowledge of the above observer. In this manner a number of readings taken with the aerial tuned were interspersed with the readings taken with the aerial earthed. Observations were made in this manner for several successive days, and, by taking the mean of each set of readings, a fairly reliable average bearing was obtained for each condition of the aerial, independent of any small day variations. The results obtained are shown in Table 4.

Table 4.

Effect on Observed Bearings of Tuning a Neighbouring Aerial.

Station observed	Wave-length	With aerial earthed		With aerial tuned		Difference due to tuning aerial
		No. of obsvns.	Mean bearing	No. of obsvns.	Mean bearing	
	km		degrees		degrees	degree
Paris ..	2·6	8	144·6	8	144·5	− 0·1
Paris ..	3·2	26	145·0	27	144·9	− 0·1
Horsea	4·5	32	218·4	28	217·8	− 0·6

In the case of the observations on Paris both the above-mentioned aerials were adjusted, as it was observed that the effect with one was very small. It is seen from Table 4, however, that the total effect of both aerials is only to produce a change in bearing of about 0·1°, and this result is consistent for both the wave-lengths used by Paris, although the actual bearings on these two wave-lengths differ owing to other causes. For the Horsea observations, however, only the nearer aerial could be brought into resonance, and this operation is seen to produce a change of 0.6° in the apparent bearing. This increased effect may have been due to the fact of the latter waves being continuous, as distinct from the damped waves used in the Paris transmission, and the effect also probably depends upon the relative directions of the aerial and the incoming waves.

A new and much larger multi-wire aerial just erected at the National Physical Laboratory has been found to produce an alteration in the bearing of Paris of 4° to 5°, when tuned to the same wave-length, although

* A. Hoyt Taylor: "Variation in Direction of Propagation of Long Electromagnetic Waves," *Scientific Papers of the Bureau of Standards*, No. 353, 1919.

† See footnote on page 179.

the nearest point of the aerial is over 120 ft. from the direction finder, and the leading-in wire of the aerial, where the current will naturally be a maximum, is about 300 ft. away. Further experiments will be carried out on this effect.

The proximity of a closed coil may affect the readings of a direction finder in a manner similar to a tuned aerial system. This question arose from the necessity of using two of the Robinson sets at Teddington in the same hut, about 80 ft. apart. Several sets of simultaneous obervations taken on these two sets, however, failed to show any consistent error at either due to the presence of the other. Some further experiments were later carried out on the effect of a large single-frame coil, 5 ft. square, placed at various distances from the standard direction-finder set. In each position the effect was tried of short-circuiting the coil and of tuning it to the incoming waves, while observations were made on the Robinson set. With a distance of 35 ft. between the coils the effect of tuning produced an error in the mean bearings of only 0·1°. When the distance was reduced to 18 ft. the effect was variable for different stations but was never greater than 0·5°.

When the single coil was brought up to within 10 ft. of the direction finder, the error produced in the bearings on the latter ranged from 1° to 2° on Paris, and from 0·5° to 1·8° on Nauen. The bearing was changed immediately the coil was tuned, there being no apparent error due merely to the presence of the coil, when this was either on open circuit or short-circuit. The bearings on the direction finder might, however, be appreciably affected by the presence of an open coil when working near the natural wave-length of the latter. The possibility of this was well demonstrated in one case where a partly-wound frame stood some 6 or 8 ft. from a direction finder and produced an error of nearly 4° on the readings of the latter on certain wave-lengths. The error disappeared when the frame was removed to a distance of 30 ft.

It was not considered profitable to carry out further experiments on the effect of tuned coils in the neighbourhood, for instance, the variation in the error with the change in orientation of the coil relative to the direction-finding set, etc. The results were sufficient to justify the practice in accurate working of keeping all frame coils at least 100 ft. from a directional receiving

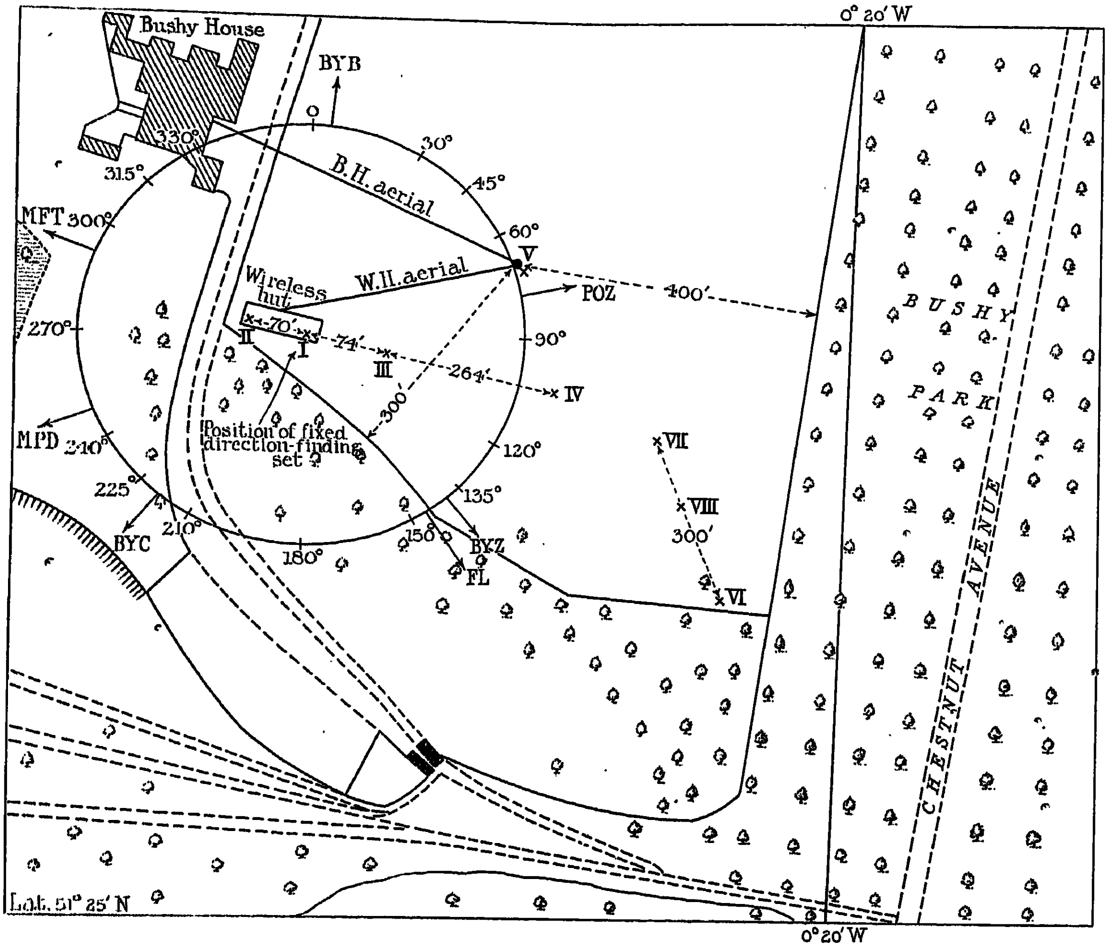


FIG. 2.—Plan of neighbourhood of wireless hut at the National Physical Laboratory, Teddington, showing aerials and positions explored in finding the effect of trees.

set, especially if both sets of coils are in operation simultaneously.

(4) Trees.

It has been known for some considerable time that the presence of trees has a considerable effect on the propagation of electromagnetic waves. Duddell and Taylor in some experiments * carried out in Bushy Park in 1905 showed that the presence of clumps of trees between a radio-telegraphic transmitter and the receiver considerably decreased the signal strength at the latter.

More recently also Squier † has shown that growing trees can be used very effectively as aerials for the reception of signals over long or short distances.

A large tree may thus reasonably be regarded as being equivalent to a vertical aerial in which oscillatory currents are induced by the arriving electromagnetic waves, and these currents may give rise to secondary effects due to induction or re-radiation. Since, however, the tree will possess a fairly high resistance, and it is naturally an untuned circuit for most wave-lengths, the presence of single, isolated trees would not be expected to have much effect on a direction-finder coil unless placed in very close proximity to the trees. With large masses or clumps of trees, however, a cumulative effect may be produced in regard to the secondary field, which may give rise to serious errors at a directional receiving installation.

Experiments were therefore carried out in the grounds of the National Physical Laboratory to obtain some knowledge of the magnitude of the effect of neighbouring trees on a direction finder. A plan view of the scene of these experiments is shown in Fig. 2. The position of the standard direction-finding set at Teddington is indicated by the point I in one corner of a large, open field bounded on the south and east by large masses of trees, and on the north and west by residential buildings and the Laboratory buildings, respectively. The nearest building is some 200 ft. from the receiving set, and the remaining buildings are at more than 3 times this distance. There are no overhead wires in the neighbourhood, and the effect of the aerials has been dealt with in the previous section. As, however, the nearest trees are within 40 ft. of the receiver it was thought that these might account for some of the permanent errors experienced at Teddington.

While maintaining set No. 1 fixed in position and taking frequent check-bearings therewith, a second set No. 2 was placed successively in the various positions indicated by II, III, IV, etc., in Fig. 2, and bearings were taken on two or three well-known fixed stations. In the first series of experiments the changes in position were fairly large, as indicated in the figure. A summary of the results of the bearings observed in each position is given in Table 5. Check-bearings were taken simultaneously on set No. 1 in a fixed position, and these showed a variation during the experiments ranging from 0·1° to 0·4°. The mean variation during each experiment was applied as a correction to the mean observed bearing on set No. 2 in each position, and this mean bearing was then corrected for scale errors. The tabulated readings are, therefore, made independent of scale error and any change of external conditions. The setting of the coil was made in each case by the prismatic compass, and is probably reliable to about 0·2°.

Table 5.

Station	Paris (2·6 km)		Poldhu (2·8 km)		Paris (3·2 km)		Nauen (3·9 km)	
Position of set No. 2	Mean observed bearing	Departure of observed from true bearing	Mean observed bearing	Departure of observed from true bearing	Mean observed bearing	Departure of observed from true bearing	Mean observed bearing	Departure of observed from true bearing
	degrees	degrees	degrees	degrees	degrees	degrees	degrees	degrees
II*	144·7	− 1·0	249·0	+ 1·3	145·0	− 0·6	76·7	+ 0·3
III*	146·7	+ 1·1	249·7	+ 2·0	146·1	+ 0·5	78·4	+ 2·0
IV*	147·9	+ 2·3	250·1	+ 2·4	147·2	+ 1·6	78·1	+ 1·7
V*	147·0	+ 1·4	247·1	− 0·6	146·3	+ 0·7	76·2	− 0·2
VII*	146·9	+ 1·3	250·2	+ 2·5	146·0	+ 0·4	78·5	+ 2·1
VI*	141·7	− 3·9	250·2	+ 4·5	141·5	− 4·1	78·2	+ 1·8

* The figures refer to the positions in Fig. 2.

These results show very clearly the effect of the proximity of the trees. The general trend is for the error in the apparent bearing to be progressive for positions II, III, IV, VII, and VI, i.e. as the direction-finder set is taken into the junction of the large masses of trees to the east and south of the field. On the whole the error is a minimum in position V, which is the point farthest from all the trees, being in fact about 300 ft. from the nearest tree. The difference in the apparent bearing at positions V and VI is seen to be over 5° for Paris and Poldhu, and 2° for Nauen. The errors on the latter station are consistently smaller than on the others, probably due to the fact that the waves from Nauen (POZ) come across the open field to the receiver, while those from Paris (FL) and Poldhu (MPD) come directly through the trees, as indicated in Fig. 2.

* W. Duddell and J. E. Taylor: "Wireless Telegraphy Measurements," *Journal I.E.E.*, 1905, vol. 35, p. 321.

† G. O. Squier: "Tree Telephony and Telegraphy," *Journal of the Franklin Institute*, 1919, vol. 187, p. 657; also *Electrician*, 1920, vol. 84, pp. 111 and 147.

Owing to the varied distribution of the trees, it is somewhat difficult to draw any conclusions more definite than the above. For example, the change in sign of the error on Paris in positions II and III, and VII and VI is probably due to the actual path of the waves through the trees. The bearing on the long wave of Paris is seen to be consistently lower than that on the short wave, although it varies somewhat for the different positions. It is possibly partly due to instrumental error, or to some other influence more remote from the receiver.

The increase in the error obtained when the direction finder is taken much closer to the trees was well

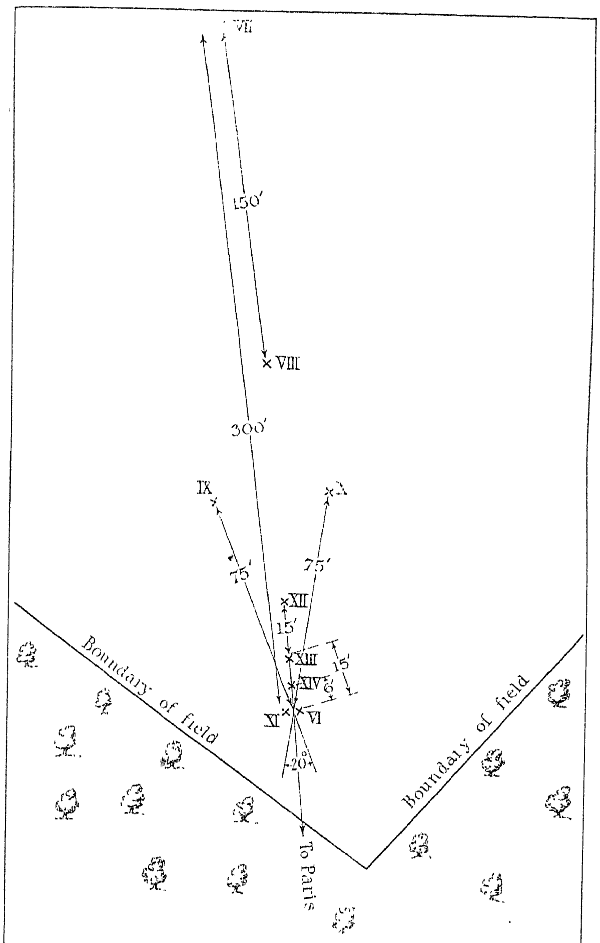


FIG. 3.—Investigation of the change in the observed bearing of Paris (FL) in the neighbourhood of position VI (see Fig. 2).

demonstrated by the second series of experiments, which were confined to observations made on Paris and carried out between positions VI and VII on a line approximately in the direction of Paris, as shown in Fig. 3. These positions are all within about 300 ft. of the trees, and the results obtained (duly corrected as above) are given in Table 6.

The most noticeable point about these latter results is the extent to which the bearing may change for

TABLE 6.

Observations made on Paris Signals in the Neighbourhood of Trees.

Position of Set No. 2	Mean observed bearing	Difference of observed from true bearing
	degrees	degrees
VII	146·9	+ 1·3
VIII	146·6	+ 1·0
IX	147·6	+ 2·0
X	148·1	+ 2·2
XII	146·9	+ 1·3
XIII	146·7	+ 1·1
XIV	144·6	− 1·0
XI	138·7	− 6·9
VI	141·9	− 3·7

a very slight change in the position of the receiving set. Thus, at positions X and XI (only 75 ft. apart) the difference in the observed bearings is 9·1°. These large changes are probably due to the difference in

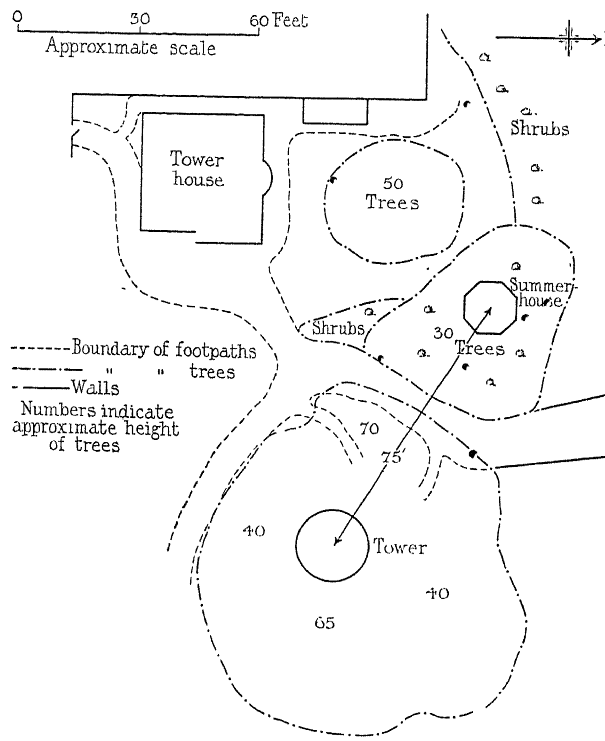


FIG 4.—Site of experiments on trees at Bristol University.

phase effects of the inductive fields from the different trees. The two sets of experiments thus demonstrate quite well that the presence of trees within about 300 ft. from a direction-finding installation may produce quite large, measurable errors in the readings of the latter. As it is possible that the error may vary with the changing state of the trees at the different seasons, the error may be a variable one and hence is to be avoided if possible.

Further observations upon the effect of trees.—At the request of one of the authors, Mr. M. G. Bennett, B.Sc., the observer at the Radio Research Board Direction-Finding Station at Bristol University, has carried out some experiments on the effect of trees on wireless bearings. The standard directional receiver at Bristol is erected on the top floor of a stone tower, about 60 ft. above the ground. The tower is practically surrounded by trees within a radius of 60 to 100 ft., and those in the immediate neighbourhood of the tower were pruned to a height less than that of the receiver. All metal work was removed from the tower previous to the erection of the set.

A plan of the tower and its surroundings is shown in Fig. 4. In addition to this set, a small single-frame coil receiver was used for observation of bearings in two positions on the ground: (1) at the base of the tower, and (2) in the wooden summer-house (shown in Fig. 4) about 75 ft. away from the tower. The orientation of these coils was carried out by means of a theodolite and is correct to within 0·25°.

Observations were made on several transmitting stations for two or three days in each position, and a summary of these results is given in Table 7. All the results obtained are correct to about 1°.

TABLE 7:

Effect of Trees on Observed Bearings at Bristol.

Station observed	Wave-length	True bearing	Observed bearings: At top of tower	At base of tower	In summer-house	Max. change in observed bearing
	km	degrees	degrees	degrees	degrees	degrees
Paris ..	2·6	127·8	127·6	127·3	128·7	1·4
Paris ..	3·2	127·8	126·7	127·2	129·3	2·6
Poldhu ..	2·8	230·6	230·5	232·9	229·3	3·6
Nauen ..	3·2	77·0	76·7	78·7	70·0	8·7
Cleethorpes	4·0	35·9	37·2	—	36·2	1·0
Moscow ..	5·0	63·8	63·8	—	64·7	0·9

The results are sufficient to show that comparatively large changes in apparent bearing are produced by a small change in position of the directional receiver, thus confirming those obtained at Teddington and referred to earlier in the paper. Further changes could probably have been produced by other movements of the receiver, but this was not considered to be justifiable owing to the scattered positions of the trees. It was not possible to make any observations with the receiver erected in a clear position on either side of this clump of trees, owing to the intervention of other obstacles, e.g. iron buildings, overhead wires, etc.

It is perhaps significant that in the majority of cases in the above table the most accurate bearings were obtained at the top of the tower, a result to be expected since the induced current in the trees (and hence the resulting field) will be a maximum at the base.

(5) BUILDINGS.

It has long been known that large buildings, hills and mountains act as partial obstacles to the passage of electromagnetic waves, and the tendency is for the latter to be deviated around the obstacle. A directional radio receiver in the neighbourhood of such obstacles would therefore be expected to give some erratic results. If the building, moreover, contains an appreciable amount of metal work in its construction, such as steel girders, lead or iron roof, etc., an error will result due to their presence, as discussed earlier in the paper. The effect of working inside a building was well demonstrated in one case, where the receiving set was temporarily erected in one of the University laboratories for the purpose of making practice observations. The errors in the readings obtained ranged up to more than 30°, whereas when the set was removed to its final position in an open field less than ½ mile away, the maximum permanent error experienced was 2·8°. In another case, however, where the set was erected at the top of a stone tower about 60 ft. high, from which all the metal work had been previously removed, the maximum deviation error experienced was about 3°.

Experiments in a large iron shed.—As a special case of the effect of a building on observed bearings, the results of the following experiments carried out in a kite-balloon shed at the Royal Aircraft Establishment, Farnborough, are of considerable interest.

A systematic investigation was carried out to determine the direction of the resultant field inside the shed by the same method employed in the investigation on the effect of trees and other experiments already described. A plan of the shed showing the positions

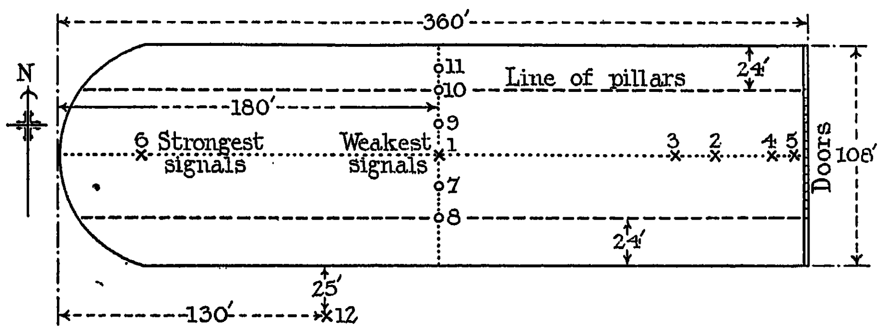


FIG. 5.—Plan and dimensions of "A" shed, Royal Aircraft Establishment, Farnborough.

where observations were made is shown in Fig. 5. Although only a rough estimate could be made of the strength of the signals received, some marked variations were noted in the different positions employed. It was found that at the centre position 1 the reduction of signals was very great, but that as either end was approached the strength of signals became steadily greater, though it was not until the set was brought actually outside the shed that the full strength was attained. Position 6, however, some 40 ft. from the "blind" end gave signals which were obviously much stronger than those at any other position. There appears to be no obvious reason for this, but it is suggested that the curved end might have had some sort of focusing action on the waves. No change in signal strength could be detected on opening or closing the doors of the shed in any of the positions explored.

TABLE 8.

Apparent Bearings observed at Centre of Shed. Position 1.

Station observed		Wave-length	True bearing	True bearing relative to shed's axis	Error in observed bearing
		km	degrees	degrees	degrees
Paris	..	2·6	139·8	47·8	+ 12·2
Paris	..	3·2	139·8	47·8	+ 15·0
Nantes	..	2·8	188·0	96·0	− 14·0
Horsea	..	5·0	202·0	110·0	− 8·0
Poldhu	..	2·8	248·0	156·0	+ 0·3
Moscow	..	5·0	64·0	332·0	− 6·0
Nauen	..	5·0	75·6	343·6	− 13·6

The influence of the shed on the apparent bearing of the station observed was carefully recorded in each case, and is here given in Tables 8 to 11.

It was thought most suitable to limit the positions explored to points on the long or short axes of the shed.

Table 8 shows the errors in the apparent bearings observed at the centre of the shed, indicating that the incoming waves are deflected towards the perpendicular to the sides of the shed; the deflection varying from 0·3° to 15°, according to the angle made by the incoming waves with the axis of the shed. No effect due to opening the door was observed on any of the stations.

In Table 9 the effect at different positions along the long axis of the shed is shown, signals from Paris only being observed. These results show that at positions other than the centre the apparent bearing is deflected towards the axis of the shed. The effect is more clearly seen in Fig. 6.

TABLE 9.

Bearings of Paris (both Wave-lengths) taken on Axis of Shed.

Position No.	Distance from door of shed (E end)	Error in observed bearing: (a) with door closed	Error in observed bearing: (b) with door open	Change in bearing on opening door
	ft.	degrees	degrees	degrees
5	3	− 21·3 (2·6 km)	− 1·6 (2·6 km)	+ 19·7
4	12	− 20·8 (3·2 km)	− 14·0 (3·2 km)	+ 6·8
2	40	− 19·8 (2·6 km)	− 15·8 (2·6 km)	+ 4·0
		− 12·5 (3·2 km)	—	—
3	60	− 3·8 (2·6 km)	—	—
		+ 7·4 (3·2 km)	—	—
1	180	+ 12·2 (2·6 km)	+ 11·9 (2·6 km)	− 0·3
		+ 15·0 (3·2 km)	—	—
6	320	− 28·3 (2·6 km)	− 27·7 (2·6 km)	+ 0·6

TABLE 10.

Bearings of Other Stations taken on Axis of Shed.

Position No.	Distance from door (E end)	Station	Error in observed bearing: (a) with door closed	Error in observed bearing: (b) with door open
	ft.		degrees	degrees
1	180	Poldhu	+ 0·3	—
6	320	Poldhu	+ 4·5	—
2	40	Coltano	− 3·0*	+ 4·7
6	320	Coltano	− 24·6	—
1	180	Horsea	− 8·0	—
2	40	Moscow	+ 25·0*	+ 26·0*
1	180	Moscow	− 6·0	—

* Indicates night reading.

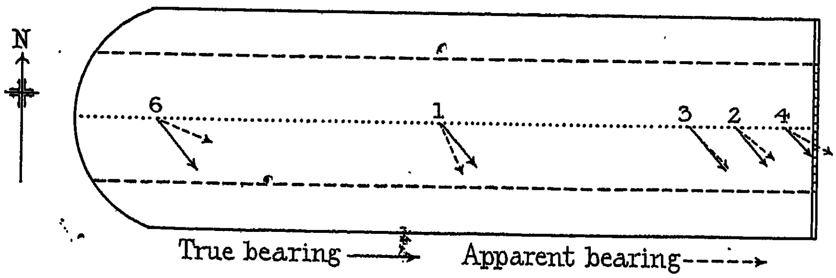


FIG. 6.—True and apparent bearings of Paris at various positions on the axis of the shed (see Table 9).

Table 10 shows the same effect occurring on a few

other stations which were observed, thus demonstrating that the results for Paris are repeated for other directions.

Table 11 gives the results of exploring positions along the lateral axis of the shed, showing that for positions north of the long axis the rotation of the apparent bearing is greater than at the centre, while in the southern positions it is considerably less. It

TABLE 11.

Bearings of Paris taken on the Lateral Axis of the Shed.

Position No.	Distance from N side of shed	Error in observed bearing (a) with door closed	Error in observed bearing (b) with door open
	ft.	degrees	degrees
11	14	+ 14·0 (2·6 km) + 15·9 (3·2 km)	— —
10	24	+ 17·7 (3·2 km)	+ 15·0 (3·2 km)
9	39	+ 18·1 (3·2 km)	
1	54	+ 12·2 (2·6 km) + 15·0 (3·2 km)	+ 11·9 (2·6 km)
7	69	+ 4·5 (2·6 km)	+ 3·7 (2·6 km)
8	84	+ 0·2 (2·6 km) − 1·2 (3·2 km)	— —
12	133 (25 ft. beyond S side of shed, i.e. outside)	+ 16·2 (2·6 km) + 17·2 (3·2 km)	— —

should be pointed out, however, that there are two parallel lines of iron pillars supporting the shed and that in Positions 7, 8, 10 and 11 they are near enough to the direction finder to affect seriously the readings obtained.

Position 12 in Table 11 was outside the shed about 25 ft. from the south side (see Fig. 5): it will be seen that here too there was a considerable rotation of the apparent bearings towards the perpendicular to the side of the shed.

A brief survey of all the results obtained in these experiments shows that, in general, the apparent bearings of the incoming signals are rotated towards the normal to the nearest plane surface by an amount which increases as that surface is approached. Fig. 6 clearly shows this. The slight departure from this rule shown in Table 11 may be easily accounted for by the pillars already referred to.

In addition, it was proved that the opening of the large doors had a scarcely noticeable effect on the bearings, except when the set was very close to them (when the result was merely what would have been predicted by the above theory), and had no effect at all on the strength of the signals. This seems to show that no appreciable extra energy comes through the doors when they are open.

CONCLUSIONS.

Owing to the great variability in the possible nature and disposition of the surroundings of a direction-finding installation, it is very difficult, if not impossible, to make general rules as to the effect of such surroundings. It is believed, however, that the results of the investigations given above are of value in augmenting the scanty evidence previously existing as to the distortion produced in the propagation of electromagnetic waves by various obstacles on the earth's surface.

The experiments themselves suggest further lines of advance, and it is proposed to continue these as soon as opportunity permits.

These investigations were carried out for the Radio Research Board by the authors under the direction of the Sub-Committee on Directional Wireless, the members of this Sub-Committee being as follows:—Mr. F. E. Smith, O.B.E., F.R.S. (*Chairman*); Mr. N. P. Hinton, B.Sc.; Mr. C. E. Horton, B.A.; Captain C. T. Hughes, M.C., R.E.; Captain J. Robinson, Ph.D., M.B.E., R.A.F.; Mr. R. L. Smith-Rose, M.Sc.; and Mr. O. F. Brown, M.A., B.Sc. (*Secretary*).

DISCUSSION BEFORE THE WIRELESS SECTION, 8 NOVEMBER, 1922.

Dr. J. Robinson: The information contained in this paper is of a type that is needed in order to attain the end for which all wireless engineers are striving, namely, that navigators shall have confidence in direction-finding. The paper shows the importance of choosing the correct site for direction-finding apparatus. An examination of the cause of errors brings several points to light. Errors may be produced, as the paper suggests, owing to the fact that some of the factors, e.g. electric force or magnetic force, are not in the direction they are generally supposed to be, while, on the other hand, errors may be due to the fact that some portions of the waves are reflected, giving, at any particular point, an effect of waves arriving from one station in two directions. That leads us to one of the experiments described by the authors. If one set of waves comes horizontally, direct from the transmitting station, and the other is reflected from the Heaviside layer, how are these two sets to be separated? In optics we have the analogy of the telescope, and it was thought that it might be possible to have a wireless telescope. It is known that for a telescope the wave-length should be small compared with the dimensions of the telescope. It is difficult to obtain a mirror or telescope with dimensions many times greater than the ordinary wave-length in wireless, which varies from 200 m. to 2 000 m; and the best thing that can be obtained is an airship shed, the dimensions of which are comparable with those of wireless waves. The experiments carried out in the Farnborough airship shed unfortunately did not give the effect of a wireless telescope. I should like to place on record one occasion where an effect was observed which appeared to indicate the possibility

of a wireless telescope effect. In an airship shed at Cranwell signals from Paris were weak, whilst those from Nauen were strong. The axis of the shed was nearly in the direction of Nauen and approximately perpendicular to the direction from Paris. Present-day direction-finding is based on the assumption that the magnetic force of the waves is horizontal. The paper gives examples which show that when the magnetic force is not horizontal the bearings are wrong. In the case of overhead wires the authors point out that the magnetic force might be in various directions. In fact, it is probable that at about 100 yards from the telegraph wires the magnetic force might be horizontal, while it might become almost vertical nearer the wires, in which case the direction-finding coil on a vertical axis would give no indication of bearing. It is to be hoped that the time is not far distant when the facts set out in the paper will be appreciated and made use of, and when navigators will know when to expect errors and when to expect accurate readings; then they will place the same reliance on direction-finding as they now place on the magnetic compass.

Mr. J. Hollingworth: In observations such as the authors have made, it is extremely difficult to modify the face of the earth to suit experimental purposes and to find sites where the only probable disturbing cause is the one required to be measured. Moreover, as the authors state, it is extremely difficult to make calculations, because the sizes and shapes of the objects dealt with are so irregular that it is impossible to lay down any mathematical law in regard to them. There are one or two special points to which I should like to call attention. At the foot of page 179 the authors truly remark that in some cases "it may be necessary to avoid all possible errors at the site of the installation." I am concerned with a rather important example of that at the moment. When making measurements on an aerial one generally allows for the absorption effect in the immediate neighbourhood, as this is involved in most methods of measuring the effective height, whereas with a coil one usually works on the area-turns of the coil, in which case nothing is allowed for absorption in the immediate neighbourhood, so that whenever a comparison is to be made between coil work and aerial work it is very important to choose an almost perfect site for the coil itself. The authors exhibited a slide showing Bushy House. I myself have an apparatus installed there to measure signal strength, and there is no doubt that the trees in the vicinity have a very considerable effect. I have frequently noticed that when the trees are thoroughly wet my readings are affected, and I think that the trees then form an almost complete screen, because most of the signals with which we have to deal come from the south through a big bank of them. I think that may also be the reason why the particular aerials shown in the diagram do not greatly affect the signals, because, after all, they are on the opposite side of the receiving set to the incoming signals. If the set had been put on the other side of the aerials, the effect would probably have been very much greater. I can confirm what the authors say about the sudden change caused by telephone wires. In my own case, I was 100 feet from the wires, and, owing to the ground not being level, my coil was on almost exactly the same level as the wires themselves. The variations obtained were only of the order of 2°, but they were quite definite jumps; they could not be explained by any general physical characteristics of the atmosphere. There is, I think, no doubt that the effects are due to the operation of the telephone exchanges; capacities which are quite negligible for telephone purposes are considerable for wireless purposes. For the latter I have always considered telephone lines to be practically earthed at the two exchanges in the immediate neighbourhood. My own results were obtained with telephone wires very much shorter, because ¼ mile away from the scene of my observations they entered a submarine cable which was practically an earth for wireless purposes. They did not, I think, extend for more than a few miles in the other direction. I am of the opinion, therefore, that it is the near proximity of wires that caused the trouble, rather than any particular length of them. There is one point which I should like to mention with regard to airship sheds. I have in mind some measurements made in an airship shed when all the signals appeared to enter along the axis of the shed—an experience contrary to that obtained by the authors. The shed in question was larger than that used by them, i.e. about 700 ft. long. It was not systematically explored; observations were not taken all over the shed. The fact that a 600-ft. airship containing a great amount of metal work was in the shed, and that the coil itself was standing practically on the keel of the airship, may have modified the conditions very much as compared with those given in the paper, where the shed was empty and it was possible to explore the whole of it.

Mr. J. E. Taylor: The paper contains the results of a great deal of work, and the most interesting feature of it, to my mind, is that dealing with variations in the apparent direction of fixed stations, which may be due to local or other causes. The only point on which I wish to comment is in connection with variations observed to be due to the presence of banks of telephone wires. Of course, it is not strictly accurate to say that these wires are earthed at the exchanges, but I think that Mr. Hollingworth has put that right. The wires are practically earthed at the stations to high-frequency currents, not as a result of switching operations but due to the fact that they are led-in in cables, and therefore for wireless purposes we can regard them as being earthed. I feel rather sceptical, however, with regard to the surmise that changes in the apparent direction are due to switching operations at exchanges, which in the case of the Slough experiment are probably quite a distance away from the scene of operations. I feel that that point, in common with many others in the paper, is well worth further investigation. I doubt whether the explanation given in the paper is correct, and it seems to me that it should be a comparatively simple matter to erect on light poles a special pair of wires which would be fixed and not subject to switching operations. Such wires must of course be fairly long, e.g. about 1 mile. If that were done

I should not be surprised to find the variations still in evidence.

Mr. C. E. Horton: I was particularly interested in the account of the results obtained on the survey ship "Fitzroy." In this case the dimensions of the coil were small as compared with those of the adjacent metal structures, which are for the most part somewhat irregular. Under these conditions it seems to me rather striking that the curve should approximate so closely to the quadrantal type. I was also rather surprised to see that its magnitude amounted to over 20°. Prof. Mesny, who did a good deal of work with small coils on board ship, usually found quadrantal errors of 8° or 10° on small ships, but in his case the coil was usually placed right aft. I should be glad if the authors would give further details as to the actual position of the coil on the ship, particularly with reference to the funnels. It is stated in the paper that the quadrantal error is independent of the wave-length. So long as the metal structure is small compared with the wave-length, and so long as dielectric currents are neglected, that would be, I suppose, in accordance with theory; but if the quadrantal error amounts to 20° or more, although it is perfectly constant and can in a sense be allowed for, there is some difficulty in making use of it. If the reading of the frame coil is uncertain to a degree or so, i.e. the amount of correction to be applied is unknown, it follows, I think, that when the correction changes rather rapidly, as it does in this case, the final result, after the correction has been made, may be quite incorrect, in fact, more so than the actual uncertainty of the reading itself. It follows, therefore, that a large quadrantal error is very undesirable. As the effect of local structures is so very important when the coil is small, it seems to indicate that what is needed is a system large in comparison with structures in the immediate vicinity. Under those conditions a sort of average effect is obtained, and errors due to small structures are very much decreased. I am thinking now of the Bellini-Tosi system which appears to offer some advantage in the case of a ship, since the area comprised by loops is very much larger, and a much better average effect is obtained. The authors remark that the quadrantal error curve is shifted along the axis some 5° or 6°, that is to say, whereas one would expect to get the zero correction for waves at readings of 0°, 90°, 180°, etc., actually there is a small correction of 5° or 6°, and that is attributed to the effect of small local structures. That again, to my mind, seems to indicate that what is needed is an aerial system much larger than the ordinary frame coil for use on steel ships.

Major H. P. T. Lefroy: Errors in direction-finding can conveniently be considered under the headings "uncontrollable" and "controllable," the latter of which can again be conveniently considered under the headings "environment" and "apparatus." This paper deals with some of the errors due to environment, and is an interesting summary of investigations carried out by the authors for Sub-Committee C of the Radio Research Board, in connection with those special errors. Their results show that, when siting and constructing a direction-finding station, it is best to give a wide berth to all possible causes of distortion, in and around the station. As regards lines, in ordinary practice one has to use electric power and light, and to have a telephone. The practical problem then raised is: Shall the lines be put underground or run overhead? I noticed that the authors' lines went past the station and did not terminate there, as they nearly always do in practice. It would be instructive if some figures could be obtained showing the difference in the errors caused by lines buried 3 ft. deep, and lines brought in 10 ft. or 12 ft. overhead, as they usually are, and terminating at the station itself. I should like the authors to say at what time of the year the experiments with trees were carried out. From the botanical point of view it would be interesting if they could take a series of measurements once a week, or once a fortnight at a certain definite spot, e.g. position XI, to find out how the errors due to the trees change with the seasons and the state of the foliage.

Mr. G. M. Wright: On page 179 the authors dismiss very summarily the question of night effects by saying that "little is known as to the causes producing these effects, though much has been surmised." Mr. Eckersley has published a paper * on the subject of night effects in which he sets forth a theory which, besides being reasonable, has the advantage of being well supported by the experimental results obtained up to that date. Since then, further investigations have been made † as to the behaviour of the cardioid diagram of reception under the influence of night effects, and these investigations have afforded the most striking confirmation of Eckersley's theory. I know of no other theory which has been seriously proposed and examined which rests on so sure a basis and is capable of affording so complete an explanation. I would also point out that the minimum of a cardioid diagram remains unchanged and correct throughout the most violent night effect and affords a practical means of direction-finding under these conditions. In fact, any directive receiving system which presents no unbalanced horizontal members to a ray incident in the direction of zero reception is capable of being used as an accurate direction-finder in the presence of night effect. I should also like to draw attention to the similarity of the curve shown in Fig. 1 (*b*) to a simple sine function. This resemblance affords a very easy method of correcting the errors when using crossed frames in conjuncton with a radiogoniometer. The method was proposed some years ago by Captain Round, and consists in placing one aerial in the plane towards which the bearings are distorted. A suitable reduction in the receiving power of this aerial will then give the required correction. Under all ordinary circumstances the correction obtained in this way is sufficiently accurate, and no error chart is required.

Admiral Sir Henry Jackson: There is a great deal more work to be done in this direction, especially in connection with short waves. I think that it would be desirable to carry out similar experiments with trees, telegraph wires and large metallic objects with

* "The Effect of the Heaviside Layer on the Apparent Direction of Electromagnetic Waves," *Radio Review*, vol. 2, pp. 60 and 231.

† "The Heart-shaped Polar Diagram and its Behaviour under Night Variations," *ibid.*, p. 394.

short waves, such as are used for navigational work. The object of the Radio Research Board is to try to define the different errors, so that we can correct our direction-finding apparatus in ships as the magnetic compass is corrected. We are now in the early days of direction-finding and I hope that in a few years direction-finding at sea by wireless will be as accurate as it is now by compass.

Major B. Binyon: I was very interested in the description of the work done on board ship, and I hope, with Admiral Sir Henry Jackson, that the work of the Radio Research Board will be further extended in that direction, because, from a commercial point of view, it is one of the most important fields in which to work. It is to be regretted that in most of the work done on ships, data for which are given in the paper, fairly long waves have been used, whereas in practice it is absolutely essential that direction-finders to be really useful should work mainly on 600 m. Mr. Horton stated that, in his opinion, better results would be obtained with an aerial system than with coils on ships. I should like to mention, in that connection, that a number of ships have been fitted with Robinson direction-finders, and the extraordinary accuracy of the results obtained is proof of the reliability of a coil system aboard ship, particularly when the exceedingly difficult conditions are taken into account—conditions far more difficult, I think, than any of those described in the paper. Again, quadrantal errors as large as 22° are referred to in the paper. I have never known such an error on a ship fitted with the Robinson system; I can recollect one case where an error of 19° was obtained, but in the case of another steamer where the conditions were similar the quadrantal error was nil. In the latter case the quadrantal error remained nil until, after a long trip, the boat was nearing home, when suddenly an error of 6° or 7° developed. No explanation was forthcoming at first, but the trouble was eventually traced to four electric leads used for emergency communications between the chart room and the emergency steering position aft. These leads were supposed to be absolutely dead, but somehow or other a fault had developed in them, and small currents from the electric light circuits leaked on to them. They were eventually shown to be entirely responsible for the error. That is an instance of the sort of problems that have to be faced in shipping work and which increase the difficulties. In spite of this, however, there is no doubt that exceedingly good and satisfactory results can be obtained with the Robinson system on board ship. The constancy of the quadrantal error is, of course, all-important and has to be very carefully watched for, but on the whole the changes are very slight. As a matter of fact, a discrepancy was observed in the case of a ship that went out quite light—in ballast—and returned very heavily laden. In that case the quadrantal error on the return journey had diminished by a small amount. Unfortunately, experimental work on ships of the mercantile marine is exceedingly difficult to carry out, and it can more systematically be done by the Radio Research Board or the Admiralty allocating vessels for the purpose. With the extended use of direction-finders, however, exceedingly interesting data of this nature is gradually being collected. I should like to support Admiral Sir Henry Jackson's suggestion that more work should be done on short wave-lengths, in order as far as possible to benefit directly the commercial application of direction-finding as an aid to navigation.

Captain C. T. Hughes: I should like to call attention to the importance of the information given in the paper from the military point of view. It might possibly be urged that a radio engineer entrusted with the installation of a direction-finder would never deliberately put up his set in the neighbourhood of trees, buildings or other wireless aerials, but in military practice it might be impossible to avoid doing so. As direction-finding is a vital part of military wireless, it is very important that one should have every possible scrap of information regarding the errors to be expected owing to the presence of these disturbing elements. It very frequently happens that a wireless officer has no choice of site in putting up his direction-finder; there are a large number of considerations, chiefly military, which hamper his selection of suitable ground. For example, it is essential that he should have a means of rapid communication, by telephone or ordinary telegraph line, with the intelligence centre to which he has to send his information. It frequently happens that it is very difficult to provide a special line for him, and possibly he has to put up his direction-finder in the immediate neighbourhood of some busy signal office where there are a large number of overhead lines or buried cables. It might be inadvisable, moreover, to put a direction-finder in an isolated field, well away from trees and buildings, from the point of view of visibility from aircraft. That is only one of a large number of considerations which must influence the selection of a site. Major Lefroy, I think, rather dismissed the possibility of errors due to the proximity of overhead lines, by assuming that the lines were the actual supply mains or line communications of the station itself, and that these are generally controlled by the officer in charge of the station and can be buried for some hundreds of yards away from the direction-finder. The officer may be obliged, however, in times of rapid military movement, to erect his set in the near neighbourhood of large permanent routes on a main road, or other disturbing factors may appear in the shape of large masses of metal such as ammunition dumps. In military wireless too, the set has frequently to be handed over to semi-skilled personnel who have had little chance of acquiring a knowledge of what constitutes good conditions for direction-finding. For these reasons we welcome any information that tends to define the conditions governing the installation of a direction-finder or gives us a knowledge of the magnitude of the errors to be expected under adverse conditions of working.

Major C. J. Aston: I should like to ask whether anything is yet known as to the effect of rivers on direction-finding. It is often necessary to erect a direction-finder in the neighbourhood of a river, which might have a straight course 3 to 4 miles in length, and might influence the direction of the arriving waves. The Army of Occupation in Germany found such conditions at Cologne.

Dr. A. Russell: Have the authors considered the effect of meteorological conditions on the direction of reception? For instance, on one side of the direction-finder there may be a shower of rain, while the other side is dry. The trees on the one side would be almost perfect conductors under such conditions, while those on the other would have a very high resistance. We know that the resistance of the surface of the earth varies to a very large extent with the amount of dew on it. It would therefore be interesting if the authors could give any information on this subject.

Mr. S. B. Smith (*communicated*): It can be demonstrated that if a directional system be constructed in such a manner that no unbalanced horizontal members exist, then abnormally polarized waves will not be received. With such arrangements it can be experimentally shown that when night effect is present the bearings are correct. The minima will also be quite symmetrical, and the arrangement provides a practical direction-finder. A number of anti-"night effect" direction-finders (which possess symmetrical minima) exist, among them being Adcock's modification to the Bellini-Tosi aerial system, and Franklin's spaced aerials (arranged in the Bellini-Tosi manner). These methods are well known and do not require further detailing, but at the same time it should be pointed out that it is quite practicable to construct a direction-finder to be quite immune from "night effect" or the closely related "aeroplane effect." In Section 3 of the paper the authors discuss tuned aerial systems and their effect when in close proximity to the direction-finder. No mention is made of the importance of the resistance of these aerials, but unless the authors give the dimensions of these aerials and their resistance the observations are comparatively useless. At a recently installed direction-finding station the apparatus is erected underneath the main transmitting aerial; if this aerial is accidentally tuned while the direction-finder is in operation the maximum observed errors amount to 30°. If the tuned aerial had a very low resistance (principally radiation resistance) the maximum deviation from the true bearing could amount to almost 90°.

Messrs. R. L. Smith-Rose and **R. H. Barfield** (*in reply*): The discussion has, in general, shown that the paper has met a real need for detailed quantitative information on this subject. There is a general consensus of opinion as to the necessity of repeating the majority of the investigations on much shorter wave-lengths, and it is intended to proceed with this work as quickly as possible. The research was inaugurated on the higher wave-lengths for no other reasons than those of convenience and expediency, since suitable apparatus was immediately available. The experience gained so far will undoubtedly prove useful in the work on shorter waves where the difficulties of accurate radio direction-finding are somewhat greater.

Mr. Hollingworth mentions a case of a large airship shed in which all the signals appeared to enter along the axis of the shed. This is exactly the conclusion that might have been drawn for the shed referred to in the paper when at Position 6 in Fig. 6, had not the results obtained in other positions been contradictory.

The results given for the experiments carried out on H.M.S. "Fitzroy" were certainly obtained under very bad conditions. The direction-finding coil system was erected in the only place available on board, being placed fairly close to the ship's funnel and the wireless cabin, and standing on the steel deck. Mr. Horton expresses surprise at the magnitude and regularity of the error curve, yet a somewhat similar curve has been given by Mr. Round for H.M.S. "Warspite," and cases are mentioned in which the error curve ranges up to 30°.* Regular quadrantal error curves have also been obtained in America when using small frame coils on board ship.† The results given in the paper for H.M.S. "Fitzroy" have been confirmed by later observations and the error has been found to be practically independent of small metal work in the immediate neighbourhood, e.g. the error remained unaltered by opening and closing steel hatch covers immediately beneath the set. The disadvantages of a large correction curve for navigation purposes are fully appreciated, but it is probable that the magnitude of the error could be considerably reduced by erecting the frame coil in a more suitable position on board and particularly by raising it several feet above the deck. The present paper is not concerned with the relative merits of the Bellini-Tosi and the frame-coil systems of direction-finding on board ship, but it may be pointed out that considerable use of the single frame has been made in America.†

The point raised by Major Lefroy as to the comparative effect of overhead and underground lines actually brought into the direction-finding station is one that has not so far received attention but is obviously important for practical purposes. It is hoped to obtain much information on the influence on the resulting errors of the seasonal change in trees from an investigation which has been proceeding for some time past, involving the daily observation of various transmitting stations in fixed positions. The influence of meteorological conditions mentioned by Dr. Russell will also be studied in the same investigation.

In reply to Mr. Wright, the authors feel bound to uphold their original statement to which reference is made. While fully recognizing the utility of the brilliant work carried out by Messrs. Eckersley, Wright and Smith, it must be mentioned that there are already some apparent exceptions to Eckersley's theory concerning variations.‡ Beyond this fact, the paper is not concerned with these night variations in the bearings observed on direction-finders. As to the use of circuits giving the cardioid-diagram reception curves to overcome these effects, this has surely never been claimed as a practical system of direction-finding. At the best, it affords a convenient means of determining the "sense" of a bearing.

That there are certain methods, theoretically sound and experimentally successful, of eliminating abnormally polarized waves is beyond question, nor can it be denied that it may be possible to construct a com-

* *Journal I.E.E.*, 1920, vol. 58, p. 243.

† See, for example, S. BALLANTINE: *Year Book of Wireless Telegraphy and Telephony*, 1921, p. 1131; also F. A. KOLSTER and F. W. DUNMORE: *Scientific Papers of the Bureau of Standards*, No. 428, 1922.

‡ See, for example, E. BELLINI: *Electrician*, 1922, vol. 89, p. 150; also R. MESNY, *L'Onde Electrique*, 1922, vol. 1, p. 501.

mercially practical apparatus for this purpose. It is merely contended that as yet this has not been done. Mr. Smith mentions two systems, those of Adcock and Franklin, but Mr. Keen in his recent authoritative work on direction-finding * dismisses the Franklin system as being "impracticable for ordinary direction-finding working" giving convincing reasons, whilst Adcock's system has never been taken up owing to its inherent difficulties. As regards tuned aerials, a record of what actually happened in one or two specific cases was thought to be of sufficient value in giving the order of the possible error to merit recording. For example, Mr. Smith's own instance is of some definite interest though it would have been of more value if he had given the distance of the direction-finding set from the aerial.

Major Binyon's request to investigate directional reception on board ship on the waves ordinarily used for ship communication is covered by the proposal to extend the whole investigation to short-wave working.

The possible effect of rivers, mentioned by Major Aston, is also a case for future investigation.

* R. Keen: "Direction and Position Finding by Wireless," 1922, p. 195.

DOMESTIC LOAD BUILDING: A FEW SUGGESTIONS UPON PROPAGANDA WORK.

By W. A. GILLOTT, Associate Member.

(Paper first received 11th September, and in final form 13th October, 1922; *read before* THE INSTITUTION 30*th November, before the* NORTH-EASTERN CENTRE 27*th November, before the* LIVERPOOL SUB-CENTRE 11*th December, before the* NORTH MIDLAND CENTRE 19*th December,* 1922, *and before the* SCOTTISH CENTRE 9*th January,* 1923.)

SUMMARY.

The object of this paper is to show in a simple manner some of the channels open to electric supply undertakings for securing the domestic load. As conditions differ in almost every district, the subject must be approached from a different angle in each case. In certain districts it might be fatal to adopt a too progressive attitude, and one must therefore lead up to the point by suggestion; in others it may be found desirable to combine the development scheme, such as an educative campaign by actual demonstration, with Press and other advertisements. These methods are briefly discussed and reference is made to the value of the load to the undertaking, and the various proportions it can take. A skeleton scheme of one year's campaign is put forward, and, in view of the decision of certain authorities to embark upon this development, it is hoped that the remarks may be of interest. The fundamental essentials on the question of tariffs, load characteristics, hire of appliances, etc., are discussed, and a chart showing one week's demand of a housing estate, where cookers, heaters, etc., are installed, is given. The advantage of an electrically equipped household to the consumer and its appeal to women, also the assistance given by the latter in achieving the object, are referred to.

FUNDAMENTAL PRINCIPLES.

The increasing tendency of the housewife to do her domestic work by means of electricity is most encouraging, and indicates that the excellent propaganda work of the Electrical Development Association, electric supply authorities, electrical contractors and manufacturers is at last beginning to show a return. These promising conditions prompt the author to offer a few suggestions in regard to domestic load-building to those engineers who have not yet attempted to cultivate this desirable and profitable demand. At the outset he would like to state that his remarks are not put forward as definite proposals as to how matters should proceed, but merely as a suggested principle upon which the framework of an organization or department can be constructed to deal with the business.

The first matter that should receive attention is the personnel. From the chief engineer to, at least, the sales representatives each individual should possess an adequate knowledge of the subject of domestic electrification before attempting to advise others. In addition, an electrical installation, complete in every detail, should be in the homes of such members of the staff to enable them to gain valuable experience and thoroughly to appreciate their operation. It would also establish a belief in the commodity and be an encouragement to prospective consumers.

It is desirable to keep a careful set of records of the behaviour of each type of appliance, of the time taken to attain certain objects, of the consumption, also of maintenance costs. By this means a valuable set of statistics would soon be collected which would be of considerable help in establishing a foundation on which to build a suitable scheme. During these observations a complete set of recording ammeter charts should be secured. If several of these are taken simultaneously, a summation curve can be plotted and accurately compared with the station load curve, to facilitate the design of a suitable tariff (if one is needed). Curves similar to these were given by the author in a previous paper.* From these earlier curves the following figures were taken: The number of units per annum per kilowatt installed was 360; the total connected load of the 13 consumers studied was 65 kW, while the maximum demand was approximately 19 kW. The amount of this load that fell on the system peak was 5 kW. The number of units consumed per annum per kilowatt of demand on the system peak was 3 240. The diversity factor was 9. Although these curves were taken some time ago the characteristics remain the same to-day, cooking conditions not having altered. The design of the apparatus is, however, improved, therefore the number of units consumed per kilowatt installed is reduced. A safe figure to adopt for estimating purposes when investigating the subject is 300 units per kilowatt installed per annum. These figures assume a normal daily use throughout the year and are sufficient to indicate that the domestic cooking load is worth cultivating.

TARIFF CONSTRUCTION AND LOAD POSSIBILITIES.

It is not intended to study the details of tariffs for this class of business, beyond referring to the desirability of a two-part scheme, with a comparatively high fixed charge, and with the charge per unit so low as to provide a satisfactory return. The author inclines to the opinion that the fixed charge should be sufficient to cover a consumer's normal lighting costs when the low unit charge is added. In other words, his lighting account would be practically identical under this tariff with what it would be under the standard flat rate which may be in operation. This provides a safeguard against supplying the consumer at a loss, and it is only upon an increased consumption that he obtains the benefit of the cheaper units.

Taking as an illustration a domestic consumer with

* *Journal I.E.E.*, 1915, vol. 53, p. 42.

1 kW of lighting installed, under average conditions his normal consumption would be approximately 300 units per annum, thus :—

Flat Rate	£ s. d.	*Two-part Tariff*	£ s. d.
300 units at (say) 8d.	10 0 0	Fixed charge per kilowatt (lighting) installed (say)	8 10 0
		300 units at (say) $1\frac{1}{2}$d.	1 17 6
			£10 7 6

The figure of $1\frac{1}{2}$d. is taken because the present tendency is to supply electricity for domestic purposes at this rate.

From the above it will be seen that the consumer's lighting account remains, for all practical purposes, unaltered. If such a consumer installs a cooker, catering for 6 persons, his consumption of electrical energy would be increased by approximately 1 750 units per annum, making his account as follows :—

	£ s. d.
Fixed charge as before	8 10 0
2 050 units (lighting and cooking) at $1\frac{1}{2}$d.	12 16 3
	£21 6 3

The average price obtained per unit will be approximately $2\frac{1}{2}$d. It is good business to prove to a consumer that his adoption of a domestic or multi-part tariff does not increase his normal lighting account, and that extravagance in the use of light is costing him only $1\frac{1}{2}$d. per unit, which can for practical purposes be ignored. He will then see that his cooking, heating or power is charged at this low rate and he will appreciate the change. The education of the consumer upon this point will be of great value, as he will learn to look upon his supply as being given at $1\frac{1}{2}$d. per unit, and regard the fixed charge as a rental. He will probably spread the news amongst his friends, and this will be good propaganda for the undertaking. Such an installation would create a maximum demand of approximately 3·5 kW, which would occur about mid-day, i.e. at a time when the majority of central stations could deal with the load. Taking average conditions at 200 volts or over, the service cable to a house with such a demand would probably be of adequate capacity, and, therefore, in such cases there would be no additional costs under this heading. It is, of course, recommended that negotiations should be commenced to induce the consumer ultimately to extend his demands for other uses, e.g. heating, water heating and auxiliaries, in which case the service cable would be made suitable. An increase of 3 kW of heating and 2 kW of auxiliaries would make but little difference to the maximum demand, this being approximately 5·5 kW, and then only in winter time, but the total consumption would be in the neighbourhood of 3 500 units per annum, representing, on the basis given above, an amount of £30 7s. 6d., i.e. an increase of £20 7s. 6d. above the ordinary lighting returns.

Taking as an illustration some 500 of such consumers on one system, the maximum load installed would be 6 000 kW; the maximum demand on the station would not, however, owing to the high diversity factor, exceed 600 kW. The consumption of the whole would be $1\frac{1}{4}$ million units, and the revenue approximately £15 200.

One of the most important characteristics of this class of business is its continuity; in contrast to the industrial load it is unaffected by strikes or lock-outs, and this should therefore increase the desire to cultivate it.

The curves on page 199 indicate the nature of the load upon the Billingham Housing Estate. These curves show the result of the demand of 25 houses only, i.e. approximately one-third of the whole village.

The details of the installation of each house are as follows :—

1 Cooker.
1 Wash boiler (10 gallons).
1 Fire.
Kettle or iron.
Lighting.

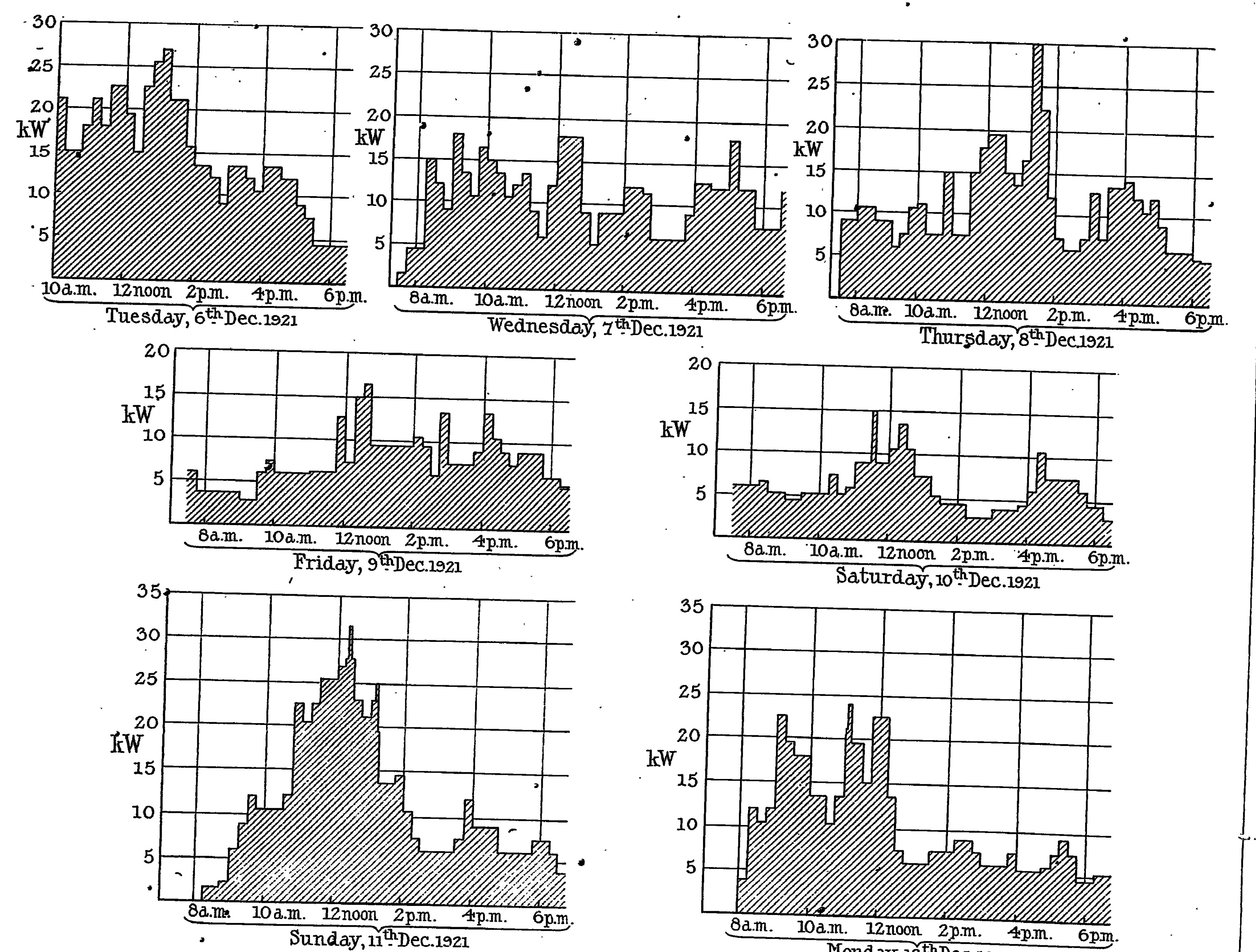
The average number of kilowatts installed at each house is 11·28, and, therefore, the total connected load is $11{\cdot}28 \times 25 = 282$ kW. The pressure at the consumers' terminals is 250 volts. It will be seen that the highest demand (approximately 31 kW) occurred on Sunday, 11th December, at 12.30 p.m. It is interesting to note that this demand lasted for only a few minutes, the average maximum demand being in the neighbourhood of 24 kW. The returns, being taken in winter time, are consequently at their maximum.

It is of interest to study the characteristics of the daily demand. As the curve shows, Sunday is undoubtedly a day when much cooking is done, and no doubt a certain amount of heating is carried on from breakfast (8.15 a.m.) to 2.30 p.m. There is a short period of rest before tea is prepared, about 4 p.m., and at 6.30 p.m. the load quickly drops to the normal lighting demand, as is the case on each day of the week.

The morning load on Monday and Tuesday is due to the wash boilers and cooking. Monday's curve indicates that the boilers are in operation soon after 8 a.m. and that the cooking load is not so heavy, as probably no mid-day meals will be cooked. On Tuesdays almost the same conditions apply, but more cooking is done, as shown by the demand from 12.30 p.m. to 2 p.m. Thursday is undoubtedly the bread-baking day, as shown by the comparatively longer period of demand. Saturday appears to be a day of "put off" meals.

The occupiers of the houses include district engineers, station engineers, engine drivers, and the usual type of individual employed upon a supply system. No other system of cooking is provided, and it is the usual practice to bake bread and cakes at home.

These curves give much information, and one is able to estimate with accuracy the size of feeder cables necessary for a district. They show at a glance how the load comes on and how it coincides with the general station demand, and they can be applied to any system for comparison. They amply prove the load to be a daytime demand, and that it is continuous, i.e. it is an everyday load. The high diversity factor is well



Chart, showing one week's demand of a housing estate where electric cookers, heaters, etc., are installed. This represents the result of a *connected* load of 282 kW over 25 houses.

demonstrated, and proves the value of the load to an undertaking.

These curves enable one to imagine the nature of the system load in the power station of the future. By multiplying these results by the number of likely consumers in a given area, it will be seen that it is possible for the domestic load in many stations to be larger than the industrial load.

The author has compared the curve for Sunday with that of a gas company's output on a similar day. The two are identical in shape, and it is interesting to relate that the value to the gas company of 5 hours' Sunday's load was equal to that of a whole week-day's combined domestic and industrial load.

In view of the importance of the domestic load, and the desirability of distributing as much information of its character as possible amongst supply engineers, the author suggests that the Institution might consider the advisability of investigating the matter in detail and submitting a report upon its findings. The Electrical Development Association have obtained certain information of a general nature, and by co-operation most valuable assistance could no doubt be given to the industry.

Turning now to commercial cooking, considerable revenue can also be secured from this source. In an earlier paper * the author gave a set of curves showing the load characteristics of four installations, including three staff-feeding kitchens and one restaurant, totalling some 452 kW connected. The total number of units consumed was 290 000 per annum, and the resultant maximum demand was 190 kW (approximately). These facts are important and demonstrate the value of the load.

It is realized that there are many small undertakings which are not at present in a position to handle a big demand for cooking and heating, and that some concerns do not encourage the business as their load is entirely residential lighting and they possibly fear that the cooking business will create a loss. It will be understood that even moderate cooking demands are not built in a day, such loads being secured by a comparatively gradual process. It is suggested, therefore, that a start should be made upon a small scale in order to gain experience in districts where the plant and cable capacity are small and the rate is unsuitable for complete cookers. It will be found that if auxiliary appliances, e.g. kettles, irons, toasters, boiling plates, washing machines, vacuum cleaners, etc., are used, their existence will have a greater effect on the financial returns than on the station maximum demand.

It is not, however, the object of this paper to discuss the technicalities of the load and its effect upon the plant and cables, but to open up various channels that may assist those who are interested in the subject to secure the business. The possibilities of the domestic field are large, and the figures and statistics given indicate a few of the results that can be obtained by negotiation.

There are, no doubt, undertakings in which the domestic load has not been encouraged, possibly because the staff have not studied the subject, or because they are uncertain of the effect of the load on their system and tariff. It is possible for concerns to obtain information, complete in every detail, as to how this load will apply to their own undertakings, and they can in consequence embark upon any such scheme knowing from the commencement approximately what the results will be.

* *Journal I.E.E.* 1918, vol. 56, p. 92.

The Consumers' Gain.

The next point of view to consider is that of the consumer. What benefit will he derive from using electrical energy freely, and will its adoption give him the service he needs ?

In the average household of six persons a maid and occasional help are employed, and the installation of electrical appliances permits a reduction of labour charges at least equivalent to the amount spent on electricity. If it should be decided to retain the existing labour, benefit is secured by the relief of heavy and tedious work, better working conditions, convenience, cleanliness and improvement in the health of the family owing to the non-polluted atmosphere and more freedom enabling them to pursue a more out-door life. Unless one has lived in an electrically equipped home it is almost impossible to realize its worth, or to imagine how many household duties entailing laborious work, e.g. clothes and dish-washing, carpet beating, wall cleaning, can be performed by a mere turn of the switch. The author is of the opinion that if men were to study the internal domestic problem more closely, or were called upon to do the actual work, the use of electrical labour-saving appliances would be greatly increased. In works or offices men adopt the principle of "Save the man and use the machine." Why should not this principle be applied at home ? The housewife has more to contend with than is generally realized, and it is only fair that she should benefit by the use of the appliances now available.

The items already stated were given to indicate, in a brief manner, the value and magnitude of the possible load. It was felt desirable to give these instances as the good load factor which domestic electrification provides when cookers and heaters are used under normal daily conditions is not generally realized.

A Skeleton Scheme of Propaganda.

The basic facts being agreed, one can now proceed to commence the campaign. There are various methods available, e.g. the local Press, mailing letters and leaflets, posters, exhibitions, showrooms, personal calls, lantern slides, etc. The amount to be spent on propaganda will doubtless be decided, and upon this will depend the extent of the scheme; the smaller the amount the greater is the care that must be exercised in selecting the medium.

As an illustration, take a town with a population of, say, 100 000, in which the sum of £500 is to be allowed for one year's advertising, it also being decided to adopt a hiring policy for electrical appliances, and to reduce the price of electricity. It is suggested that a staff conference should be held, at which the programme could be discussed to ensure that the campaign should be commenced with at least the majority of the members enthusiastic and co-operating to reach some definite

goal, say 250, 500 or 1 000 kW connected in a specified period.

In the early stages it will probably be found advisable to adopt the least line of resistance by encouraging the existing consumers to increase their demand, and there are other obvious reasons for this procedure.

A saving of expense will no doubt result if a mailing campaign is arranged to coincide with the dispatch of the quarterly accounts, the backs of which should convey a suitable message drawing attention to the reduction in price of electricity, and other special features, and a small booklet should be enclosed to suit the particular period of the year.

Municipal undertakings owning tramways have the advantage in being in a position to exhibit showcards or notices in the tramcars at possibly no expense beyond the printing, thus securing valuable publicity. Lantern slides can be exhibited at the local kinema houses or theatres each week throughout the year. Those slides would doubtless be changed, say, four times per annum at the change of each season.

A productive and economical exhibit can be given by establishing a "Comfy Home" exhibition. For this the loan of a house (which can usually be secured free) is obtained, and the house is then equipped in every detail, thus enabling the appliances to be shown in actual use under normal conditions. If properly handled no difficulty will be met in securing the co-operation of the various trades concerned, i.e. furnishers, decorators, builders, etc., each performing his part at his own cost. Suitable invitations should be sent out, and it is recommended that the editors of the local Press and certain influential people should be invited to an electrically cooked meal before the exhibit is opened. This will probably ensure a valuable report appearing in the Press, and interest will be stimulated.

The electrical contractors of the town could be encouraged to participate in the scheme by dressing their showrooms with domestic appliances so as to fit in with the scheme, and their clients should have every facility offered them to inspect the home, when all details would be explained to them, the contractor being, of course, properly dealt with in regard to any sales effected.

It cannot be too strongly urged that an exhibit of this nature should be arranged to appeal especially to women; their needs and desires should be studied in every detail, and great care should be taken to give them all the information possible. In addition, they should be encouraged to handle the various devices for domestic use.

It may be found desirable to arrange for private demonstrations on selected days, for the benefit of those who would not care to discuss matters when other visitors are within hearing distance. This will ensure more rapid progress being made. It is advisable at the outset to secure the interest of women, for they will then make it their business to persuade their husbands to complete the transaction. The author's intention is not to suggest that one's efforts should cease at this stage, but to point out that women's influence will be of considerable help in effecting sales, and that its cultivation is worth while.

General Electrical Exhibition.

It would be helpful if an electrical exhibition could be held, at which manufacturers and contractors would co-operate. A large hall is not necessary for the purpose, as quite good results can be secured with a moderate expenditure, and for small towns a week's duration will probably suffice. Endeavours should be made to show all classes of operations that would be of the greatest assistance and interest to the inhabitants. Arrangements might be made with advantage to establish a series of self-contained exhibits, such as a model kitchen, with cooker, water heater, clothes washer, etc., in operation; a shoe-repairing shop with the stitching machine and sole-polishing iron electrically operated; a confectioners' bench with cakes and chocolates made electrically; a small electric laundry; and a day and night nursery complete with all requisites from those for rocking the cradle and warming the milk, to an electric sewing machine for making babies' clothes. The object should be, as far as possible, to show something working, as it has a peculiar fascination to the visitor and of course demonstrates in a practical manner the many uses to which electricity can be applied.

It is not suggested that such an exhibition should be held each year, but only as an attempt to popularize some special feature as mentioned above. It will be readily understood that if exhibitions of this nature are held in the same town at too frequent intervals they will become uninteresting and will thus be of little value.

Details of Expenditure.

The various channels in which the sum of £500 could be expended having been briefly stated, the following will be a guide to their respective costs. In analysing these figures it must be appreciated that the leaflets, posters, show cards, etc., would be purchased through the Electrical Development Association, thereby effecting an appreciable saving. The number of consumers has been assumed at 3 500 for the purpose of making this estimate.

Total yearly cost of mailing campaign at each quarter day (four per annum).	£	s.	d.
Differences of postages when sending accounts	58	8	0
Leaflets	40	0	0
Cost of printing only on back of account forms	5	0	0
Other items.			
Lantern slides, rent at 4 theatres, 52 weeks each at 4s. (average price)	41	12	0
Cost of slides, say	5	0	0
Show cards and posters (these would be exhibited upon the undertakings' own property, viz. vehicles, buildings, cable tents, etc.)	10	0	0
"Comfy Home" exhibition	70	0	0
Electrical exhibition	150	0	0
20 000 assorted leaflets (average price £3 per 1 000)	60	0	0
Local Press advertising (say 10 insertions) ..	60	0	0
	£500	0	0

As may be readily appreciated, this schedule can be improved upon; it can also be further sub-divided or cut down if a less costly scheme is desired. It suffices, however, for the immediate purpose of promoting discussion.

Showrooms.

The use of showrooms to electric supply undertakings is more appreciated at the present time, but it is essential that, to ensure success, these should be properly managed. If there is sufficient space to do so it will be desirable to show different systems of wiring and lighting, and various types of apparatus in as nearly as possible their normal conditions. Interest will be created if certain days or weeks are given up to specific functions, e.g. washing, ironing, cooking, vacuum cleaning, table appliances, etc. Actual working exhibits are preferred, as visitors will be more inclined to discuss proposals than if "dead" shows are given.

It is suggested that all such work of a homely nature should be conducted by a lady demonstrator in such a position that the operations may, upon certain occasions, be seen from the street.

The outside sales representatives should be kept informed as to the callers from their districts, and as much information as possible of their visit should be given to save much ground being covered twice; the consumer appreciates this and it places the salesman upon a better footing.

Hire of Cookers.

It is not proposed to discuss fully the internal organization necessary for the hire of cookers, but it might suffice to state that if a rental of 20 per cent per annum on the net cost be established it will provide a satisfactory return on the capital invested and will cover the cost of maintenance. Local conditions will, of course, influence these rentals, and in certain districts a much higher return can be obtained.

It must not, however, be overlooked that the mere fact of the cooker being installed and used earns a revenue which without such facility may not be obtained. It is suggested that a lady cook demonstrator should make periodical calls upon the consumers to render efficient cooking service and to ensure that the consumers are securing the best possible results.

Those undertakings where the cooking load is not required so rapidly as when simple hire is established may conduct a hire-purchase scheme, which does not involve as much capital outlay and which will encourage the consumer to handle the appliances with greater care. There are, of course, political conditions that prevent certain undertakings from supplying appliances under this plan, but the formation of a company to conduct such work, as mentioned by Mr. C. H. Wordingham at the Sanitary Congress, would overcome the difficulty and enable a business profitable to all concerned to be established. It is hoped that this suggestion will be followed up and become an accomplished fact.

The chief engineers of central stations usually have their time fully occupied upon the engineering side of the business and have not much opportunity of concentrating their attention on the commercial end. The author hopes, therefore, that these suggestions will be acceptable to them. He has given a good deal of consideration to the domestic load question and fully realizes that these remarks only touch the fringe of the subject. In suggesting that central station engineers should cultivate the domestic load, the author realizes that there are many difficulties to be overcome; he is of the opinion, however, that the examples and curves shown are sufficiently attractive to encourage one at least to give the business a trial. The mere fact that difficulties are present invites investigation, and is it not correct, that almost every "worth while" object is reached by overcoming difficulties? There are thousands of pounds' worth of business to be secured in almost every district. The public are in a receptive attitude towards electrical appliances, and there are three essentials to enable this harvest to be reaped:

(1) The will to do;

(2) Absolute belief in the commodity; and

(3) Adequate support for the campaign by the giving of sound service.

While the paper has dealt mainly with the electric supply aspect, the principles are applicable to either manufacturers or contractors, and contributions to the discussion by the latter will be extremely valuable.

In conclusion the author would like to express his thanks and appreciation to Mr. W. F. T. Pinkney of the Newcastle-upon-Tyne Electric Supply Company for his valuable assistance in supplying the figures relating to Billingham and for the loan of the ammeter chart from which the week's curves were plotted.

Discussion before The Institution, 30 November, 1922.

Mr. L. L. Robinson: Those of us who are really anxious to sell "service" to the public from our supply of electricity must feel greatly indebted to the author for reading his paper at this most opportune moment. The public mind, which has heard so much of "therms," was never better tuned for the reception of the all-electric domestic message. There must be an abundant demand for the supply of electricity before it can be cheap and plentiful. The best way to make it abundant is to sell as much as possible to each consumer: make each service do its utmost. Do not let the consumer be satisfied to use only that which can never be sold to him cheaply, namely light, but see that it pays him to use electricity for every possible domestic service. In my opinion the most important information disclosed in the paper is the Billingham load curve and the deductions made from it, with which I concur. Unfortunately we have not only to convince the public that we wish to give them something worth having in the shape of electrical home labour-aids; we have also to convince our colleagues that they can do the same at apparently a very small price per unit and at the same time do good business for the undertakings for which they are responsible. The Billingham

load curve must tend to dissipate their fears that cheap units will cause their plant and mains to be overloaded. The curve proves conclusively, at any rate for that case, that the domestic load will not materially affect the peak demand. That is the conclusion about which I have long been convinced, perhaps imaginatively rather than by scientific measurement. To create new business one must have imagination to enable one to look ahead. Do the job and examine its scientific aspects afterwards. However, blocks of all-electric houses are now being connected to my mains and these will enable me to collect data which, I anticipate, will confirm the Billingham data and show that the characteristics of the south are akin to those of the north. With regard to tariffs, I realize that the perfect tariff must be arrived at by evolution. The two-part tariffs in use to-day are tending in the right direction; but the unit rates are too high for the all-electric home service, including heating and hot water, though quite low enough for mere cooking to pay the consumer to use electricity. This is because the majority of consumers to-day are not electrical "whole-hoggers" and they are offered a rate which suits the faint-hearted best. I believe for the moment in a multiplicity of tariffs, each simple in itself, to give the consumers something to choose from, always provided that the flat rates are not so low that certain consumers are supplied at a loss; but I think the ideal tariff for the "whole-hoggers" could be worked out on lines which were suggested to me in a recent conversation with Mr. A. F. Berry. In consideration of the consumer agreeing to use not more than one gas boiling-ring and not more than one coal fire, and to use gas, liquid and solid fuel for no other purpose in the service of his house, the following rates will be charged: A rent per kilowatt per annum, say £x, the consumer's maximum demand being restricted by a limiter which will interfere with the supply when the agreed demand is exceeded, and a unit rate only fractionally above the undertaking's fuel cost per unit sold, say ¼d. to ½d. per unit. It is difficult to decide exactly what the charge per kilowatt should be. The actual demand at the worst may be made up of, say, ½ kW of lighting load, with practically no diversity, and 4½ kW or more of cooking load, etc., which may have a diversity of 6 to 9. With such a service the size and design of the consumer's installation would be unlimited. He would have one price for current for all purposes, and he could keep within his stipulated demand by switching off something he did not want at the moment, such as a fire, sewing machine, vacuum cleaner, etc., and unnecessary lights when the cooker was on. All night, and at many other times when nothing else was being done, he could divert his power to the hot-water storage tank, so that he could dispense with gas and solid and liquid fuel, together with all the dirt and inconvenience that those antiquated household commodities bring into the house. It is surprising how much coal and gas cost in an ordinary middle-class house. Generally this saving alone will be more than sufficient to pay the electricity undertaking's kilowatt rent, and the unit bill at ¼d. to ½d. will be small for all the advantages which are obtained in the all-electric home. If a consumer must have a coal fire, let him have it and pay for it as the luxury item, regarding electricity as the necessity.

Mr. A. F. Berry: The lines on which Mr. Robinson has spoken suggested themselves to me when considering the big water-power schemes in America, New Zealand, etc. There are the capital charges, and there is a class of customer who wishes to pay for what he uses, and not a penny more, and therefore it has always seemed to me that the first step to take is to engage a representative to carry out propaganda work on behalf of a full electrical service. If this representative points out that the *total* bill as well as the coal and gas bills will be greatly decreased if the consumer adopts electricity almost exclusively, I have no doubt that the consumer will be willing to adopt electrical service. I have sometimes been asked by appreciative consumers who have had electric installations in their houses for some months, why they had not been approached before. In conclusion, I submit that it is in the power of the electrical industry to pay such salaries as will attract the kind of man who will form a valuable connecting link between the supply undertaking and the consumer.

Mr. J. W. Beauchamp: The electrification of the home has become a subject of such importance that I suggest we can regard it as being properly within the scope of the Institution work. The physical characteristics of the supply of heat, light and power to thousands of homes will have an important bearing on the development of power stations and supply networks, and will be as worthy of careful study as many other questions which have been considered here. Obviously the author's principal object is to draw attention to the diversity of the domestic load; his charts and information make the paper most valuable. We have to convince supply engineers that the load has, and as it grows will continue to have, the important characteristics revealed in the paper. In many cases fear exists that to cultivate domestic business in a large way at rates which will satisfy the public may entail loss owing to great additional investment being required. It is necessary to show that this is not the case, and figures which I have received bear out those put forward by the author. It should be noted that the curves in the paper refer to a group of 25 houses. We have had many from single houses, but these group results are important and more of them will be welcomed. In advocating the electric method of cookery we should do well to maintain that valuable feature of the electric cooker as we know it, the independence of the various working items. We can encourage the public gradually to discard the idea of centralized cooking as practised on the coal range, a heavy apparatus doing a variety of jobs and one in which heat losses are immense if only a portion of the fuel duty is required to be performed. It is noticeable that in American practice there has been great development in the use of small cooking apparatus, e.g. grills, light ovens and other appliances. This method must secure a very high diversity of demand. The customer's investment on apparatus may be greater than where a range is used and everything is done in the kitchen in a centralized way, but although the units per kilowatt of connected apparatus are probably

lower, the units per kilowatt on the peak are no doubt greater than with more centralized methods. On page 198 the author mentions that at $1\frac{1}{2}$d. per unit all cooking in a certain establishment is done for 5s. a week; he could deduct from this two to three tons of coal a year, when the additional charge for cooking the food in the electric way would be some 4d. or 5d. a day. I should like to point out that the average cook-general costs, in wages alone, 34d. a day; an addition of 12 per cent to that covers the cost incurred by using electricity in place of coal for cookery, a small increase for the improved service, greater comfort and cleanliness and the help which that method in the kitchen gives to the whole of a household relying upon one servant or upon the unaided efforts of the mistress.

Mr. W. R. Cooper: I suggest that all propaganda work such as is mentioned in the paper should be undertaken by women and not by men. Women are very conservative, and they can be converted to new methods much more readily by other women who are in a position to appreciate difficulties that are not apparent to men.

Mr. W. R. Rawlings: The author has, I think, shown that current can be produced at a low price, and there are plenty of manufacturers able to provide the apparatus, but it is the public who wants both, and neither the supply station engineer nor the manufacturer is in a proper position to deliver his goods to the consumer; the contractor is the man who should be called upon to carry out that part of the business. The author, however, suggests the employment of a staff of representatives to tour the country and effect sales. I maintain that what is needed is co-operation between the supply station engineer, the manufacturer and the contractor. If this is obtained the industry will progress very much faster than it is doing at present. Many contractors have sunk large sums of money in showrooms, without any assistance from the supply undertakings, who should assist by giving a rebate to foster exhibitions of apparatus. Although the supply engineer is quite willing to put down large sums of money for advertisements, he will not, for some unknown reason, give the contractor proper assistance. Contractors as a body are anxious to combine in tackling this most important subject of bringing home to the public the advantages of using electricity for purposes other than lighting.

Mr. A. C. Cramb: In the paper the necessity of the sales staff taking electrical apparatus into their own homes and gaining experience with them is referred to. It is, however, difficult to convince the electricity supply undertaking on the point, and although the station engineer may be in some cases blind to the possibility of developing this side of his business, in many cases he is severely handicapped in this way. The author puts forward a suggestion for tariffs on lines recently adopted by the Croydon Corporation electricity works. We came to the conclusion that the average amount paid per consumer for lighting was about 15 per cent of the rateable value of his house. We were at first in doubt as to whether to adopt as a basis the rateable value or the amount of floor space, we eventually decided to adopt the former as being more reliable. In the case of business premises we took the number of kilowatts of installed lighting capacity and found that this worked out at about £16 per kilowatt. We instituted these alternative rates with a running charge of $1\frac{1}{2}$d. These systems were put into operation at the end of the summer, but the response was very small indeed. I am convinced that the two-rate tariff is the correct method of charging, but I am equally convinced of the difficulty of demonstrating its advantages. I find from experience that if the advantages can be explained to the consumer, say a shopkeeper,—that he can switch on his lights at any time of the day if it is dull, that it will only cost him $1\frac{1}{2}$d. instead of 7d. or 8d. and that he can leave the lights on during the evening—he will adopt this tariff. Many supply companies, both private and municipal, make practically no effort to advertise electricity and put forward its advantages, and it is astonishing that so little effort is made in this direction. I should like to say a few words in regard to the Electrical Contractors' Association, referred to by Mr. Rawlings. A large number of undertakings in this country are now only allowed to hire out apparatus; they are not allowed to sell it outright or on the hire-purchase system, and the Electrical Contractors' Association is responsible for that state of affairs. I put it to them that it is necessary for them to co-operate with the supply undertakings and to justify the position they have taken up. I am convinced that the present position is a great handicap to the development of electricity, and I hope that the Electrical Contractors' Association, which I believe is now in a strong position, will take up this question of co-operation with supply undertakings. In one district in the United States, approximating in size to Croydon, the supply undertaking has just completed a month's propaganda for the sale of domestic washing machines, with the result that 250 have been sold. If that can be done in America by a supply undertaking, surely electrical contractors should be able to do much the same in similar areas in this country. Unless the Electrical Contractors' Association advise all the contractors in an area to work together and co-operate with the supply company, it is impossible to make much progress. I hope there will be a great deal more done in this direction, and I am anxious to help in every possible way. What the author says in regard to the effect of the cooking load on capital cost affects this matter indirectly. We find in a residential district, where the length of the mains is a serious item, that in the case of three-wire cables the size of the middle wire will certainly have to be increased. With a lighting load the consumers can be balanced on the two sides of the system, but that cannot be done with electric cookers unless the distributors are large. The cooking load will be very big, and it will lead to a great deal of trouble. We have, however, experienced many difficulties in developing lighting and power, and there is no reason why we should not overcome the cooking difficulties in the same way as we did the others.

Mr. A. N. Rye: My remarks will refer to the point of view of the smaller undertakings. As Mr. Cramb mentioned, we have experienced trouble with the

middle wire, but that is a technical point, and I do not want to deal with that at the moment. We do not attempt to encourage the use of the larger apparatus. The real point is that the smaller undertakings cannot afford sufficiently attractive rates, and it seems to me that those who cannot afford attractive rates should concentrate on smaller apparatus. In a number of small companies with which I am associated, 8 000 pieces of small apparatus * have been connected in under four years, which is conclusive evidence that electricity is extremely popular with the consumer. That has been done on rates which are frankly not cooking rates at all, but very much higher than those which have been mentioned, yet I believe that everybody is satisfied. There is quite a large field in domestic load on a small scale for small undertakings. We have also tried hiring, but without much success, so far as our group of companies is concerned. We sunk about £3 000 000 in hired installations and apparatus, but a very high rental is required to cover depreciation and obsolescence, and the consumer will not pay the figure of 20 per cent mentioned in the paper. We have also tried the two-part tariff and found it very effective. In one undertaking 65 per cent of the revenue from users other than power consumers is derived from the two-part tariff, and only the balance from a flat rate, which I think is proof that the two-part tariff can be developed by enterprise. I am of the opinion that the smaller companies must wait for the larger ones to lead the way in regard to large apparatus, and then, if the results are sufficiently good, it will be time for the small undertakings to consider whether they will relay their mains, an operation which in most cases will be necessary. Under present conditions a small undertaking cannot cater for large apparatus unless a supply in bulk is available and the distribution is by alternating current so arranged that large consumers can be supplied from the high-tension main through their own transformers.

Mr. W. J. Thorrowgood: One speaker has mentioned the figure of £72 as the probable total cost of electricity for all purposes per annum, per house, but those who can afford to pay this price are few. If the use of electricity for lighting, heating and cooking is to be encouraged, it is necessary to find out what the consumer needs and meet his wishes, including the cost. It seems to me that there is a mine of wealth for supply companies in the smaller houses of the community, and if electricity were supplied to such houses a great deal of good would be done. If the tariff be reduced to, say, ½d. per unit, the resultant load will necessitate a great many super-stations all over the country.

Mr. P. M. Baker: In my opinion the propaganda which is of most importance is that which touches the consumer's pocket. It must be remembered that it is far from easy for the central station engineer to deliver heat units, produced by the combustion of fuel in a generating station, at a price which will compete with the direct production of heat in a coal range of good design, used in as efficient a manner as possible. When coal (or even gas) cooking devices are installed the advantages must be very real if the householder is to be induced to displace them in favour of electrical appliances. Even when installed, the full advantage of the use of cooking devices may not be realized, as servants do not always use them carefully or efficiently. The cook who is accustomed to the coal fire and knows that she has to light it some time beforehand in order to cook a joint, may treat the electric cooker in the same way, or she may forget to switch off when the job is done, thus not giving the electric cooker a chance. The all-electric house is a very attractive idea, but the lack of standardization of plugs and sockets and the difficulty of getting replacement parts for burnt-out apparatus are serious disadvantages which call for attention.

(*Communicated*): The difficulties mentioned above were founded on personal experience. As, however, my remarks were kept as brief as possible and may therefore have been misunderstood, it seems desirable to amplify them slightly. It follows from the first part —that dealing with cost—that the supply authority which undertakes a cooking load must: (*a*) aim at the highest possible generating and distributing efficiency; (*b*) offer power on a carefully worked-out tariff; and (*c*) adopt some scheme, such as hiring, which will relieve the householder from the capital cost of installing appliances that will be of no service to him when he removes to another area where the voltage is different. In many areas supply engineers have taken these steps and are meeting with considerable success, but such conditions are by no means universal. The advantages and disadvantages depend on the circumstances of each special case; thus, the most difficult householder to convert is probably the one whose kitchen range has to be kept going all day long for heating purposes. I do not think that my views are at variance with those of the author, and I put them forward in order that he may indicate how he would meet the difficulties which I have raised.

Mr. H. T. Young: Much has been said on the development of the domestic load and I hope that, now the Institution has interested itself in the matter, some action will be taken. The gas companies are at present carrying out much propaganda among doctors and architects, the latter for the reason that people are just beginning to change houses again in a general way. There is no doubt that it would pay us to give professional men current and service at low prices; money spent in that direction would be well invested and we should save it over and over again in our advertising propaganda. How can we get the men in our own industry to use electricity for all purposes? Many electrical engineers are using gas, and the gas companies can prove it to the prospective electrical consumer. We must pay attention to that point. An enterprising manufacturing firm has recently made the suggestion that we should do something to get the men in our own industry to use electric cookers, by reducing the price of such apparatus to them. Electrical contractors will no doubt be pleased to carry out the installations more cheaply,

* The apparatus connected from January, 1919, to October, 1922, included the following: Fires, 2 400; irons, 2 531; kettles, 566; boiling rings, 340; vacuum cleaners, 296; fans, 200; toasters, 208; ovens, stoves and cookers, 101; grills, 57; coffee- and teapots, 44; hot-plates, 42; milk- and water-heaters, 29; egg-boilers and saucepans, 34; sundry, 121.

or possibly at cost price, and if the supply companies will let them have the mains run into their houses without charge something can be done. I think it would be an advantage if the supply companies would generally adopt some multi-part tariff or contract rate. Thirty years ago few houses were wired for electric lighting. Many of those houses have since been occupied by six or seven different families, and the installations have been so altered that they are of no use to-day. New tenants often require structural alterations to be carried out, and frequently the houses have to be rewired. That is the time to put in a heating installation. Often we are told that the expense is too great, but a plug in each room for the heating appliance, and one main cable and one meter would be a great advantage on a contract rate. I feel that co-operation immediately between manufacturers, contractors and electric supply undertakings will be profitable to all concerned.

[Mr. Gillott's reply to this discussion will be found on page 216.]

North-Eastern Centre, at Newcastle, 27 November, 1922.

Mr. W. F. T. Pinkney: We have long recognized in Newcastle that the domestic load is a promising one, but we have not pushed it with the utmost vigour until recently, as we were more or less standing alone in past years, and had no very clear idea at first of the effect of the load on our mains, etc. We knew also that cookers would be greatly improved in design, and in the early days consumers for domestic electricity were rather hard to obtain. Consequently, the selling of domestic electricity was relatively costly. Domestic users, however, if hard to obtain, were at least easy to retain. The position is now changed. We know fairly accurately what is the demand which the load makes upon distribution; in addition, apparatus is improved, and consumers are easy both to obtain and retain. The author's figure of 300 units per annum per kW installed for cooking is rather on the high side for an average figure. Improvements in cooker design should have the effect of increasing the average consumption rather than of still further reducing it, as there is still a tendency to use the electric cooker as an auxiliary to a coal range, and improved design will increase the use of the former and decrease the use of the latter. The author's suggested principle of tariff-making is quite correct, but he has omitted to point out that the great advantage of a two-part tariff to the supply authority is that the fixed charge provides for a minimum annual revenue, whereas the minimum charges provided by statute are generally quite inadequate to meet the costs of availability of supply. I will show a further curve illustrating the demands on another all-electric village where the occupants are not in any way associated with the electrical industry, are of the working class, and have no special concession with regard to tariff, and the demands and consumption follow those of the Billingham village very closely indeed. When the domestic load is built up there will be greatly increased demands for large generators, cables, transformers, switchgear, protective devices, meters, wiring and accessories. In fact, it means an enlargement of the industry. Every individual member in the industry ought therefore to interest himself in domestic electrification, and we who are doing all we can to promote it find unfortunately a great deal of lethargy displayed within the industry, and there are many cases in this district of important electrical officials using electricity for lighting, but coal, gas and any other alternative for other domestic purposes. It would almost appear as if men were deliberately retarding the wheels of progress within their own industry. It is clear, therefore, although it may seem absurd, that much of the propaganda work has yet to be done amongst electrical men. The author's skeleton plan of campaign follows very closely the lines adopted in this area. He points out the advantage of a proposed financing company in London to assist supply authorities: there is and for many years has been a similar company in Newcastle.

Mr. W. Cross: During the past few months, thanks largely to the propaganda work of the Electrical Development Association, more attention has been paid to the selling side of our industry which, in the past, has been somewhat neglected by most engineers, though it is probably equally as important as technical matters. The figure of 300 units per annum for each kW installed for cooking, given by the author, does not seem to agree with the formula previously published, i.e. 1 unit per person per day. Assuming that a 4 kW oven is employed with a family of 5 people, 1 200 units will be used according to the new formula, and 1 825 units according to the old. I should be interested to know the total consumption of units per house per annum at Billingham, and also what current is used during the night. The tariff suggested by the author appears to be a fair one. If the heating load increases, however, a capital charge will surely be incurred through the need for additional copper in the mains and extra plant which will have to be taken into account in forming the tariff. It is, however, desirable to keep the cost of current as low as possible for heating, even if the cost of current for lighting is higher. I do not find the labour-saving argument to be very helpful, as women are conservative and, unless they do their own work, do not worry over efficiency (as understood by engineers): probably if men investigated matters, as suggested by the author, the labour-saving argument would lead to greater results. The author infers that the larger proportion of the actual propaganda work shall be carried out by the supply authorities; I certainly agree that they should bear the greater proportion of the cost, as probably 75 per cent of the profit arises from the sale of current, but I think that they could co-operate more fully than in the past with contractors and retailers, who act as unpaid canvassers for the sale of current and are frequently in closer touch with the consumers. I consider it essential that any scheme

of selling should be arranged mutually (or that the supply authority should at least let the contractor know its plans) so that similar statements and arguments may be used to the consumer. Sometimes unwittingly, contradictory statements are made which prevent a sale being completed, and by combined effort more business may be obtained for everybody. I believe that continuous demonstrations in a permanent model house would lead to increased business, and would not in the end be much more expensive than spasmodic efforts lasting a short time in various houses; this should be undertaken by the supply authority as an advertisement for the sale of current, as only one efficient demonstration would be profitable in any but the largest towns. It may be necessary to hire cookers or other devices costing over £10 at present, but I do not think it is desirable or necessary to let on hire cheaper articles, such as irons, kettles or fires. In selling cookers, one is usually met with the question of the provision of hot water which is usually supplied from the cooking range. I should be glad if the author would state where full information can be obtained regarding the alterations needed (and the cost of the same) to enable the kitchen fire to be dispensed with. A pamphlet on this subject showing details of various suggestions would be of great interest.

Mr. P. F. Allan: As one of those who endeavoured to introduce domestic electric cooking and heating in the early days (about 1908–10), I have lively recollections of the difficulty caused by the first high cost of the apparatus, and the subsequent frequent and costly renewals of elements, etc. It is gratifying to know that we are now to some extent overcoming both of these difficulties. No electrical engineer who has considered the question at all carefully can fail to realize the tremendous importance of the possible load, both to the supply authorities and to the manufacturers. Following the precedent of some of the electrical Press, Mr. Pinkney has complained of the fact that some electrical engineers have failed to use electrical apparatus. There is, however, something to be said on the other side. Assuming in the first place that the electrical engineer in question is able to get a house in a district where electric supply is available, he soon begins to realize why electric cooking and heating have not made more headway in this country. The prices charged for current in the majority of cases make any but occasional heating by electrical methods an impossibility for a man of moderate means. Cooking is not handicapped to the same extent, but if on an old system our electrical consumer may find, as I recently did, that the amount of load to which he is limited makes the installation of suitable apparatus impossible. In my particular case I have used electric cooking and heating apparatus wherever possible since 1908, and yet in a district supplied by Mr. Pinkney's company, and where in any case gas apparatus has to be bought outright and is not supplied on hire, I have been forced to install gas for cooking in place of electricity. I fear that, even nowadays, very few supply authorities consider it necessary to encourage their own staff to use electrical apparatus by helping them either with wiring or the supply of apparatus. In the early days to which I have referred there were, I believe, only two authorities in the country who pursued this policy. With regard to the design of cooking apparatus, I am convinced that a great deal more could be done to produce devices in which the benefits of the electrical methods are given their full scope in order to save time and add to the cook's comfort. There is no necessity to follow obsolete gas- and coal-oven practice.

Mr. W. C. Lambourn: From the commercial aspect the paper is particularly interesting to the lighting engineer, but none the less to the mains engineer. The latter has his part to play in the attractiveness to the consumer. Progressive municipalities and companies must meet the new demand. This obviously means capital outlay, but inasmuch as the new load promises to yield a return far exceeding the liberally estimated lighting load prior to the advent of domestic load, the outlay will be more than justified. Further, the once idle copper in the daytime will be carrying a load similar to the evening load. Where existing networks are fully loaded, the renewal of mains necessitated will have a two-fold purpose, as it would allow for automatic mains maintenance, which, owing to the age of many networks, would avert probable serious breakdowns and expenditure. I think that this latter course is more desirable than laying separate mains to meet this special load, which would increase the length of mains to be maintained for the one purpose. I think that careful consideration should be given when laying new mains to see that the class adopted lends itself as far as possible to the simplest form of service connection, in order to allow of the least possible cost, thereby making the charge to the prospective consumer a minimum, which, it will be admitted, is a very important item in propaganda work. The design of many networks, allowing for the lowest possible cost of the service cable, makes the charge to the consumer prohibitive, and profitable load is lost. The work of the mains engineer therefore affects the propaganda work considerably, as the invariably first question of the prospective consumer confirms.

Mr. A. G. Shearer: It is surprising to find in the paper no reference to the electric heating of water for domestic purposes, as it is obvious that if consumers have to use coal fires for heating water they will naturally use the same fire for cooking. In such cases, all that can be hoped for is that electric cooking will be used as an auxiliary. It has been the common practice for some time to supply electric heaters for domestic water service at rates approximately one-quarter to one-third of the rates for cooking and heating, provided the water-heating load is a flat demand over 24 hours, and usually consists of a heater of a capacity of 500 to 750 watts. Many of the hot-water installations in dwelling houses are not now arranged in the best manner for using small heaters continuously. Supply authorities should study the question of meeting a continuous and steady 24-hour water-heating demand at a rate which would not only be remunerative to themselves but make water-heating an economically desirable proposition to the consumer; such load need not be metered, as a flat rate proportional to the size of heater could be employed. Hot-water cylinders equipped with

electric heaters must be efficiently lagged and be of sufficient capacity to enable the necessary heat to be stored in the cylinder overnight, to meet the usual demands of the household during the day. I am of the opinion that, given a lagged cylinder of a capacity of, say, 40 to 45 gallons, the temperature of the water need not be raised above 120° F., and at that temperature the radiation losses would be negligible compared with those of the same heat input to a small cylinder operating at a temperature of 160° F. to 170° F. Until the domestic hot-water supply is satisfactorily catered for by supply authorities, electric cooking cannot be so profitably operated either by the consumer or the supply authority. Although the advantages of electric cooking do not fall short of other methods, the addition of economical water-heating facilities is bound to enhance the advantages of the electric service.

Mr. P. Ward: The figure of 300 units per kW installed is fairly accurate, but errs, I think, rather on the high side so far as small households are concerned, for the cooker installed will probably be somewhat larger than is actually necessary for the number of persons catered for. For instance, in a household of, say, 6 persons, a cooker having a total loading of 6–7 kW would be installed and the figure quoted would be about correct. In a household of 4 persons, however, a similar cooker may well be installed, and in such case the consumption will be found to be about 260 units per kW. With regard to diversity factor, the curves in the paper refer to a group of 25 houses. If further groups of 25 were taken there would be found a diversity as between those groups, so that the ultimate factor of a large cooking load would be greater than that for the 25 houses. When connecting a domestic load the question of balance will probably require attention first, and it appears advisable for a record of apparatus connected to all distributors to be kept. In many ways a hiring scheme is desirable. It will be found that the undertaking is better able to keep in touch with a consumer using hired apparatus than with one using owned apparatus. Suppose, for instance, that an oven element fails. If the cooker is hired the hirer will soon advise the undertaking, but if the cooker is owned the repair may be put off from day to day and the housewife or cook, failing to get the good results which we claim she ought to get, will become prejudiced against electric cooking in general. An instance came under my notice within the past few days where a cook was dissatisfied with an oven, and had been so for some time. On getting in touch with the owner he agreed that we should examine it, and some of the elements were found to have failed. These were replaced, the cook is now pleased and the oven, instead of being worn out as the cook thought, is giving good service. We have in this district a large number of cookers out on hire and are sending cookers out at a quicker rate than ever before. The rentals are reasonable and such as consumers are quite ready to pay, despite the fact that they are higher than the rentals of gas cookers. When considering the effect of a cooking demand on the maximum demand of a station, it may be found that the time of the former varies on different networks according to the class of resident in the locality. In cases where more than one network is supplied from one station, this further increases the diversity of the demand on that station, and also the amount of cooking apparatus which can be connected without extra expenditure on plant.

Mr. F. W. Muncaster: The subject of the paper is one which is exercising the minds of many engineers at the present time. It is beginning to be realized that consumers' business should be dealt with by specialists, and not by any odd man on the undertaking who may have the time to spare. We may congratulate ourselves on being among the pioneers of active propaganda in this direction. I trust that the paper may bring home the fact that the domestic load has possibilities which are capable of dwarfing power loads in any district. The process will, however, be a gradual one and the new conditions can, in consequence, be met as they develop. The curves and figures relating to Billingham should be taken as being on the liberal side, owing to the fact that the tariff enjoyed by the consumers, who are all on the power company's staff, is not an economic one. Nevertheless, the results are quite satisfactory from a mains point of view. The maximum demand is 11 per cent of the connected load, and the average maximum demand is 8 per cent of the connected load. On another housing scheme with almost identical equipment to the above but supplied under an economic tariff, the maximum demand is 8 per cent, and the average maximum demand is 5 per cent, of the connected load. Referring to the remarks on page 200 under the heading "The Consumers' Gain," I would remark that it is difficult to prove that the electrification of a house, where only one maid is kept, can reduce the domestic labour employed. Electrification does, undoubtedly, lighten labour, but it cannot eliminate the human element entirely. The author suggests the enclosure of leaflets with the quarterly accounts. I would ask him if he has had any experience in this direction, and, if so, what results were obtained. I can hardly conceive that the moment of receiving a bill is a propitious time to suggest to a consumer that he should adopt means to increase it. I am of the opinion that it is worth the extra postage to make the appeal at some other time, and, in order to make the same as effective as possible, to write personal covering letters drawing attention to special points in the advertising matter enclosed. With the remainder of the paper I am in complete agreement and I trust that the outlines of the scheme may be taken up and amplified all over the country. It is only by determined effort that we can hope to make substantial progress, for it must not be forgotten that we have a powerful opposition to combat.

Mr. T. Carter: This paper is far more a purely commercial one than a technical one, and I should like to make a few remarks from the point of view of the consumer who, amongst others, is to be the subject of the proposed propaganda. The author says that it is good business to prove to a consumer that his adoption of a domestic or multi-part tariff does not increase his normal lighting account, but if the figures quoted in the paper are to be taken as representative of the average domestic tariff, I fear that it will be difficult to convince me of this. My average consumption shown by my lighting bills during the past two years

is about 130 units per annum, and mine is a house where there is about 1 kW of lighting installed. This means that I am using only about 43 per cent of the amount that the author says I ought to be using, and if he proposes to charge me on the basis of his view of my requirements and not on the basis of what I am actually using he will increase my lighting bill out of all recognition, and I shall be found unwilling. The ordinary consumer will object, too, to be told that the cost of wastage or extravagance is so small that it can for practical purposes be neglected; he may rightly tell a supply company advancing that plea that if a cost of 1½d. per unit is negligible for wasted light it is also negligible for useful light, and they had better omit it from his bill altogether if they care so little about it. The great lack of the paper from the point of view of propaganda is that it does not give any simply stated costs of doing things by the use of electricity. A gas company will tell me that I can heat a room at a cost of so much an hour, and I find that their figures are reasonably correct and reliable. Something of the same sort is wanted to convince the non-technical person that it will pay him to put in more electrical appliances than he has had before, and the settlement of the whole affair really rests on a question of the cost of working and the cost of installation. What, for example, do the Billingham consumers pay per annum for the fairly extensive installation that they find in their houses when they go into them? Do they pay at the same rate as I should pay at if I put in the same appliances as they possess? Or have they preferential terms that make it worth their while to use electrical appliances in a way that I could not think of doing? At present, on a rough estimate, I think that I am paying about £20 per annum for my whole consumption of coal, gas and electricity: how much should I expect to pay if I did everything electrically? If convincing data of this sort could be given to those who ask, would there not be a great response? At present we are apt to be told that, being electrical engineers, we ought, for the sake of our industry, to install these things and on the ground of expediency stand any extra cost there may be, but are we, as trained persons, to allow ourselves to be persuaded on those grounds? If the supply companies think it so much worth while to have electrical engineers living in all-electric houses, had they not better come along to us and make it worth our while to give them this advertisement? Surely a good advertisement usually means that the advertising medium receives something for it. We await their proposals.

Mr. A. W. Crompton: None of the previous speakers appears to be concerned with the matter as dealt with by me, namely, the supplying of the large and—no doubt as a result of the author's endeavours and the consequent discussion—the rapidly increasing demands for heating and cooking supplies from consumers on networks which were originally laid out for lighting and small power supplies only. One would gather from the paper that, due to the large diversity of cooking, very little increase in the capacity of the mains would normally be required. Referring to the charts on page 199, it would be of interest to know what demands are experienced after 6.30 p.m., as in every case with the exception of Wednesday (when the load reached 12·5 kW) the demand at this time was very little more than that which would be due to the lighting only. I understand that the houses at Billingham have also coal fires and therefore, being small houses where no maid is kept, it would hardly appear likely that much use will be made of the radiators. I am of the opinion that in larger houses the heating would be much more regularly used and therefore the capacity of the mains, having regard to the existing allowable voltage variation according to the Board of Trade Regulations of ± 4 per cent, is soon reached, as heating under such conditions very frequently overlaps the purely lighting peak. It is hoped that further tests and records similar to those shown, but where a bigger proportion of heating is connected, will be made in the near future and thus enable new networks to be laid out or existing ones to be strengthened as economically as possible.

[Mr. Gillott's reply to this discussion will be found on page 216.]

Liverpool Sub-Centre, at Liverpool, 11 December, 1922.

Mr. H. Dickinson: In every trade list and circular many new forms of apparatus are given, thus showing that the manufacturers have made up their minds that there is good business to be done. The author mentions many ways in which the domestic load can be developed and I think we must all agree with the suggestions which he makes. The difficulties facing electric supply undertakings are, I think, two. In the case of a d.c. supply such as we have in Liverpool, where we supply very long distances from our substations, we are bound to find trouble in maintaining the pressure at the ends of the distributors. A big campaign for the development of the use of domestic appliances is of no avail until we have some method of dealing with the load which it will give. We have been considering for some time the best method of putting ourselves in a position to deal with this load, which we hope will in time be a very large one. Where an a.c. system is adopted it is a comparatively easy matter to employ additional substations, but when a new d.c. substation, costing many thousands of pounds, has to be installed, it is a very costly matter. After considering the matter very carefully we decided in the meantime to put in automatically controlled substations, and we hope by this means to handle the domestic load as it grows. If the experiment is not satisfactory and we have to revert to a three-phase system it will entail the scrapping of the whole of the present mains, and we are naturally not anxious to do this. I quite agree with the author that we want a two-part tariff, a fixed rate and a low running cost. It remains to decide what the fixed rate is to be based upon. The rateable value system is not by any means ideal. It has the disadvantage that in the better-class areas in a town the fixed charge bears a higher

proportion of the total cost than is the case in the poorer districts, with the result that in the better-class districts the fixed charge will amount to a higher figure than the lighting charge would be on the flat rate, whereas in the poorer districts the fixed charge may be less than the cost for lighting. This difficulty might not be serious if the consumer equipped his house throughout with domestic appliances, but in the early stages where the consumer installs only a small amount of apparatus the position becomes a hardship. If the tariff is based on the kilowatt basis, as the author suggests, it means that the supply undertaking will have to check the number of lights every year to see whether the consumer has added to his installation. If this is not done the consumer may be getting more light at a rate lower than that to which he is entitled. I should like to see some fixed basis adopted which would require the minimum of checking. Has the author ever considered the area occupied by the house or, say, the number of rooms in a house, as a basis? In a scheme of this sort the various types of houses would have to be divided into a number of categories, possibly half a dozen. The author mentions that he does not propose to deal with tariffs, but it would be of great assistance if he would give us any experience he has had, because a simple and satisfactory tariff is badly needed, and if we had that I am quite sure we could get the business. On page 197, the number of units per kilowatt of demand is given as 3 240, but on page 200 another case is given of 290 000 units with a maximum demand of 190 kW, which works out at 1 526 units per kilowatt of maximum demand. If the figure of 360 units installed, given on page 197, is taken and a similar figure for the instance given on page 200, the ratio of the maximum demand to the kilowatts installed is 1 to 3 in one case and 1 to 9 in the other. Can the author explain this? The author refers to the desirability of interesting the ladies in this class of work, and I fully agree with him. I think that if the housewife knew what amount of work she could save, she would do all the canvassing necessary. I think that it is generally appreciated that there is an enormous demand to be catered for, which will take time to secure.

Mr. J. E. Nelson: In my view there are two conditions necessary for successful domestic load-building, i.e. cheaper current, and cheap and good appliances. Without this combination I believe that a great deal of time may be devoted to propaganda with very little result. I think that the real problem for the supply engineer is to decide whether the demand, when created, will be a profitable one; if we want it we *must* offer cheaper rates and, if we can afford to do this, the domestic load will build itself without any very elaborate organizing effort being necessary. The best propagandist is a satisfactory service, which cannot be given without reliable appliances. The author has rather concentrated on the cooking side, but I have found that electric heating, while equally profitable to the supplier, is more easily introduced to the home by reason of the relatively cheap apparatus obtainable and its more obvious advantages. When the electric habit is thoroughly established, cooking may become general, but, from the point of view of propaganda work, I believe heating to be a safer recommendation to the domestic electricity user than cooking. However, I do not think that we shall approach the usage common in America unless we can supply the domestic load at much cheaper rates than are usual in this country. Taking the published rates of 10 undertakings in South-West Lancashire and Cheshire, the lowest heating and cooking rate is 1½d. and the highest 4·4d., while the majority are not less than 2d., and at these rates my experience is that electric heating and cooking is a luxury—quite worth paying for by those who can afford it but rather out of reach of the type of consumer for whom the supply authority must cater if it is really to dislodge the gas suppliers and put electric heating and cooking in the same position as electric lighting. The author has estimated 1¼ million units from 500 consumers with a maximum demand of 600 kW on the station, which means a load factor of nearly 25 per cent and, if we can feel assured of this load factor, anything from 0·75d. to 1d. would be a fairly profitable rate. At the lower figure, at least, the rate would need little in the way of external propaganda to recommend it. Under these conditions reliable appliances would sell themselves and help to build up the load. I believe that a low flat-rate is more likely to attract the domestic consumer than even a more favourable two-part tariff which is difficult to explain to the housewife, and I do not care for any two-part tariff which is not based on measured maximum demand. All others if they are successful result in the increased sale of units at a low rate; the low rate may well be offered in an understandable form. The electric iron is a valuable propagandist but many makers spoil an otherwise good job by providing a poor connection for the flexible. Every small electrical trouble tends to shake the confidence of the user in all electrical appliances, and a consumer who has used an iron for 12 months without any trouble is more likely to install cooking and heating apparatus than one who has been bothered with short-circuiting flexibles. Irons, radiators and boiling rings can be purchased fairly cheaply, but the full electric cooker—which comes into direct competition with the very much cheaper gas oven—must, I think, be reduced in price if it is to become an article of general use. The mechanical details in small domestic appliances are frequently faulty, especially at the terminals, and if manufacturers would pay more attention to these points and supply an article less easily damaged and more easily repaired, they would help the supply undertakings to foster the domestic load desired by both. While, under favourable conditions, I see no great difficulty in building the domestic load, the policy of domestic load building by encouraging heating and cooking is not quite so clear, at the present time at any rate. During the past few years the cost of appliances has put the extended domestic use of electricity rather out of court, but even if a spontaneous demand had arisen many supply undertakings have not a suitable distributing system in being to meet increased demands without considerable additions to mains and services, which it would have been foolish to undertake at the prices ruling until recently. This, no doubt, partly accounts for the slow progress

made in recent years, but cable costs are now coming down to a figure at which one may hope profitably to increase or extend the mains system to meet additional domestic uses. I think that there are good prospects of increased sales in the domestic field in the near future, especially if the load factor of the supply proves to be anything like that suggested by the author's curves and figures, which will justify the cheaper rates suggested.

Mr. S. E. Britton: My house has been completely electrically equipped for more than 10 years, and I am quite satisfied that the results that can be obtained for lighting, cleaning and cooking cannot be obtained by any other means. There are, of course, one or two difficult problems in connection with the supply of electricity for domestic purposes. These are, as mentioned by Mr. Dickinson, distribution and tariffs. I quite agree with the author's point of view regarding showrooms, advertising, exhibitions and other means of giving publicity to the value of electricity in the home. The one unsatisfactory feature of publicity propaganda is that it is extremely difficult to gauge the actual amount of business obtained by such means. Any developments which take place after publicity are naturally attributed to it, whereas it is possible that some of the developments might have taken place without any effort on the part of the undertaking. For that reason I do not believe in spending large sums of money; frequent, inexpensive reminders are probably all that are necessary to achieve the objects in view. On the question of tariffs I quite agree with Mr. Dickinson that it is essential to have a two-part tariff in connection with the supply of electricity for domestic purposes. It does not seem to be very important whether it be a kilowatt charge, a maximum-demand charge, a two-rate meter, a charge based upon the rateable value of the property, or a charge based upon the floor space as in Dundee, for meeting the standing charges, plus a low price per unit. All these methods have their good and bad points, and I do not know of any two-part tariff which is absolutely correct. It becomes a matter of expedience, and so long as a tariff is in use which enables the business to be obtained on a profitable basis, and the consumers are reasonably satisfied with the cost, it is not of great importance which of the foregoing methods is adopted. The diversity factor of 9, referred to on page 197, is a very encouraging achievement. If the author can obtain additional instances to confirm this very high figure, the fear which is frequently expressed in connection with small undertakings as to the inability of their systems of distribution to cope with domestic electricity supply, and the cost of larger mains will soon be forgotten, and every undertaking would soon strive to obtain a substantial domestic load. Another matter which, in my opinion, is an appreciable drag upon the development of domestic electricity supply, is the attitude of the Electrical Contractors' Association. I have not yet been able to see the logic of the Association's attitude towards the selling of electrical apparatus by municipal authorities. In the case of electricity supply companies the Association do not attempt to control the sale of electrical apparatus and the wiring of consumers' premises by such authorities, but as soon as undertakers who are local authorities embark upon such work, the contractors attempt to make themselves heard. They entirely ignore the fact that prior to the supply there are no contractors in many of the towns, and although the undertakers invest large sums of money in promoting the supply they are asked to await the pleasure of others to come along and provide the needs of consumers in the sale of apparatus and the wiring of consumers' premises. Undertakings which submit to this cannot develop as rapidly or be of as great a benefit to the inhabitants of the town as those which do undertake every possible work in the interest of both consumers and undertakers. It is only necessary to observe the achievements of the gas supply industry to realize the extent to which the electrical industry suffers by the refusal of electricity supply undertakings to sell apparatus and carry out wiring work. On the question of hire and hire-purchase, it is very often advantageous to develop the use of a particular piece of apparatus by supplying on hire, but the opportunity should also be given to consumers to obtain the apparatus on hire-purchase or to purchase outright in the first instance. The paper does much to remove the objections which have been raised in the past to the development of domestic electricity supply, and I think it has come at a very opportune moment and at a time when station engineers may anticipate considerable business from the supply of electricity for domestic purposes.

Mr. O. C. Waygood: The financial aspect of the problem is what the public will require information about, and propaganda work of the nature outlined in the paper will not, I feel, be very convincing. Let us assume that it is desired to install a 2 kW radiator, and use this to the extent that the drawing-room coal fire could be eliminated. A coal fire of this description would consume 1 cwt. of coal in 60 hours which, with coal at 45s. per ton, would cost approximately 0·5d. per hour. To make the electric fire equal to this in cost of running, energy would have to be supplied at 0·25d. per unit, compared with 2½d. (the figure quoted in the paper). In addition, the maintenance charges due to the elements fusing would have to be met. With regard to cooking, I give below relative figures of the price of electric and gas cookers, and their cost of hire.

Cooker	List price	Cost of hire per annum
Electric	£22	20 per cent = £4 8s. (See page 202)
Gas	£10	3 per cent = 6s.

From this comparison I estimate that with electrical energy at 0·5d. per unit, and gas at 30d. per 1 000 cubic feet, cooking becomes a financial proposition. The author refers to the present tendency to charge 1½d. per unit, but can this figure be taken as an average charge? Experience suggests that the inclusive figure is much higher. These facts must be faced and dealt with in any propaganda programme. Modern examples of huge business enterprise have been built up by

catering for the masses, and if the small consumer is to be encouraged to cook and heat by electricity the supply must be available at a reasonable charge. I maintain that if the supply authorities set themselves out to do all in their power to provide electricity at a price comparable with that of gas, the "valleys" of their load curve would soon be filled up. It is necessary to impress upon the minds of the public that the power obtained from electricity is far more conveniently handled than that obtained from gas. Dr. Ferranti once remarked: * "The smoke nuisance in our cities will be abolished as soon as the people realize that a pure atmosphere is worth paying for." But the present cost is too high. If it is impossible to get cheap energy, efficiency with reliability should be the aim of manufacturers of domestic appliances. Several tests have been made in the Laboratories of Applied Electricity of the University of Liverpool in order to arrive at the efficiency of apparatus used for raising water to the boiling point, and it is interesting to note that with the immersion-type heater, under ideal conditions, the efficiency is 90 per cent. The efficiency of the well-known immersion-type element heater averages about 80 per cent under normal conditions. With the stan-

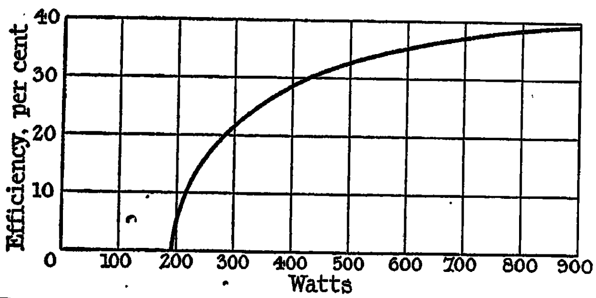


FIG. A.—Efficiency tests on a 0·75 kW flat-ring type boiler, boiling 1·6 pints of water.

dard ring-boiler type of about 0·75 kW capacity, the maximum efficiency was 38 per cent (see Fig. A). These figures show that in order that customers may get the best results, the immersion type is the one that the manufacturers should standardize for kettles. It would be interesting if some further tests could be carried out with a view to obtaining the efficiency of other types of domestic appliances. This is very important and will be more so if the cheap unit is not available. The author's statement that the consumer should be taught to believe that he is only paying 1½d. per unit, whereas in reality he is paying 2½d. per unit, is not good business, and certainly will not encourage it. Let us give the public reliable figures as to what the use of electricity means to them financially, instead of disguising the information or making the figures mean something more than they do.

Mr. E. Moxon: I quite agree with the author that it is absolutely essential that an experienced staff should be available for any campaigns launched, also that this staff should have absolute confidence in the electrical appliances that it is proposed to press for sale or hire, as the case may be. They should have good organizing ability and be tactful, to enable them to deal satisfactorily with the matter. The author gives a figure of 300 units per annum as the average demand in houses for lighting purposes. I am inclined to think that this is somewhat high for large houses, but that it is nearly correct for smaller property. I do not agree with the combined tariff that he mentions, for the following reasons. Take, for example, a consumer having 1 kW of lighting installed and radiators amounting to 10 kW in all (the radiators being used during the winter time only), consuming 300 units per annum for lighting and 1 000 units per annum for heating, and against this take another consumer having 1 kW of lighting installed and a 1 kW radiator used regularly during the summer and winter, and consuming the same number of units for lighting and heating as in the previous case. Although the average cost of current per unit consumed is the same in each case, it will, I think, be admitted that the second consumer is much more profitable to the supply authority than the first; in fact, the author's suggested rate on the combined charge in its present form destroys the object of the maximum-demand system and is little better than a maximum-demand charge for lighting with an independent flat-rate for heating, with the saving grace that it only requires one meter with common wiring for all purposes. I should prefer a similar form of tariff with a fixed charge per kilowatt of maximum demand, having a minimum annual payment against this portion of the rate to cover the standing charges suggested for the lighting installation, together with a low flat-rate per unit consumed, reducing either by a sliding scale or discounts, applying only to a certain consumption per kilowatt of maximum demand, the lower rates to apply successively after calculating progressively the charges due first on the higher rating. Such a tariff would require the addition of a demand indicator to that suggested, but only one meter, whilst the wiring could be common for all purposes. This would give advantage to the consumer with the better load factor and encourage the use of electricity for all purposes, particularly regular heating during the summer months, which in a purely residential town is much desired. With regard to the domestic load on Sundays, the author would, by reference, find that the conditions which he mentions apply chiefly to industrial towns and not to those of a purely residential character. I think that the day will come when electricity will be used for all purposes in preference to coal or gas, and anyone dealing with this subject must take into account the advantages derived from the convenience, handiness and cleanliness obtained when using electrical appliances, as an offset against any slight increase in running costs, whilst the decreased annual expenditure on decorations, carpets, upholstery, etc., will be considerable.

Mr. A. S. Wilson: I should like to say a few words from the manufacturers' point of view. Our ultimate goal is, of course, the consumer, and I feel that there is a tremendous field awaiting us for the sale of current and appliances as soon as our combined efforts have impressed on the consumer the efficiency and convenience of domestic electric appliances. This necessitates increased

* See *Journal I.E.E.*, 1914, vol. 52, p. 36.

propaganda in respect of the domestic load, and in regard to advertising I consider that the supply authorities can still do a great deal, as the consumers look to them for information rather than to the contractor or the manufacturer. In this connection I feel that much could be done by the supply authorities if their representatives, such as meter readers and inspectors, who regularly visit consumers, were well instructed as to the possibilities of this class of load and were to take all favourable opportunities for pushing this propaganda work amongst the actual consumers. The difficulty of a manufacturer of cooking apparatus in discussing domestic load-building is that it is at once assumed that he is financially interested. This is to some extent true, but at the same time it must be remembered that the manufacturers and sellers of appliances are doing all they can and spending all the money they can afford on exhibitions, fitting up showrooms, etc., and general educational work amongst the public. I consider that this expense should not be confined to any one of those who will benefit by the increased use of electricity for domestic purposes. In other words, the cost of selling to-day, particularly in this line of business, has reached a very high figure and it requires to be spread a little more fairly over those benefiting from the sales of both apparatus and power. The public are beginning to show a keen interest in the benefits arising from the use of electric supply for heating and cooking, and the curves given in the paper appear to show that this load is a paying proposition and also prove conclusively that the load does not coincide with the lighting peak, the fear of which has apparently influenced certain supply authorities against encouraging the development of this load. Another direction in which they might further this cause was suggested at a meeting of the Electrical Development Association in London, i.e. that the supply authority might strongly urge on each new consumer that a reasonable number of power or plug points should be initially installed with a view to the extension of this load, as such advice would be more readily received from the supply authority than from the contractor. There is no doubt that every consumer will eventually use one or more domestic appliances and will then congratulate himself upon having these plug points already installed. The majority of existing installations can already carry two or three times the amount of load at present connected, as there are a number of small appliances such as irons, boiling rings, kettles, vacuum cleaners, etc., which are available and can be operated from existing points now supplying only, say, a 30-watt or 40-watt lamp. These convenient appliances consume, say, 500 to 600 watts and the general extension of their use will almost invariably lead to the adoption of heavier cooking apparatus, provided the supply authorities offer a reasonable tariff and maintenance service to meet the same. From the remarks made in the discussion by representatives of the supply authorities it is very encouraging to note that such a service is being generally considered, and I think that further advantage might be taken of the resources of the Electrical Development Association who are showing a very lively interest in this matter. The lectures being given under their auspices are doing much to bring home to the sellers the amount of work which has yet to be done before we can secure a demand that will justify even one-third of the firms now interested in electrical heating and cooking devices remaining in the business. I consider, however, that the close co-operation of all concerned would result in a tremendous influx of business from this field as soon as the public are made to realize the saving in labour to be derived from the all-electric home.

Mr. R. H. Watson: From the electrical contractor's point of view the author's suggestions for domestic load-building propaganda are very valuable. The contractor is the best canvasser the supply authority has, as his problem is to persuade people to adopt electricity for every purpose. I should like to offer one or two suggestions with the view to making it easier and cheaper for consumers to install power-consuming devices. In Liverpool the supply authority lays a main into a house to deal with at least 5 kW. Usually the consumer starts with a lighting load only, and the contractor fits service switches, fuses, wiring, etc., for a 10-ampere load, and the supply authority fits a 10-ampere meter. When the consumer wishes to have power for heating or cooking the contractor has to tell him that the service switches must be changed for those rated at 25 amperes. The cost of this change is often more than the actual wiring to the power-consuming point. I think that the supply authority might require a 25-ampere service always to be fitted; if this were done the contractor would gain by not having to stock 5-ampere and 10-ampere fittings, and the supply authority need not stock 5- and 10-ampere meters. The consumer would then be able to obtain his extra wiring at less cost. If the supply main is always installed for a minimum of 25 amperes it would be reasonable for the service switches, etc., to be of the same size. This is, of course, assuming that the charge for current, either for lighting or heating, is a flat rate. The rate for charging is really not within the contractor's province, but from my own experience I would say that a flat rate is desirable, as it is much easier to get the consumer to understand it. I think that, owing to the demand for electricity now being universal, the supply authority does not need to offer separate rates, and that a mean rate could be found for all purposes. In the case of three flats which my firm recently wired, if the consumer's requirements for power and lighting had been met at separate rates it would have necessitated the installation of 8 meters. I think that the author's fixed charge per kilowatt on the two-part tariff is too high. In my own house with an annual consumption of 200 units for lighting, and 200 units for power, at the current flat rates the total cost was only £7 2s. 6d. As regards the author's suggestion of municipal showrooms, contractors would have no objection to this, provided that sales were not effected direct with the public. The showroom should not be run for profit, but should be a charge on the electricity department. One speaker in the discussion expressed surprise that the Electrical Contractors' Association objected to municipalities running showrooms and selling to the public, claiming that the supply

undertaking was best able to serve the public. In reply to that I would say that the Association object to municipal trading, for the same reason that any other trading sections of the community would object if the municipality started in competition with the ratepayers. In conclusion I think that propaganda work would benefit if the electrical departments of municipalities held occasional informal meetings with the contractors in their districts and discussed propaganda work, as I feel sure they would receive some useful information from contractors.

Mr. H. P. Tavernor: I have nothing to add to Mr. Nelson's remarks, but I may say that in my district where the average house has only 10 to 12 lights it would not be advisable to have a two-part tariff. I think that an electric fire, a kettle, and a boiling ring are far better than a cooker in this size of house, and the consumer should be encouraged to add these, and so make up a good power load. In my opinion the ordinary lighting and power rate is by far the best, as the two-rate tariff is too complicated.

Mr. J. H. Collie: It seems a very unbusinesslike arrangement to have large power stations which are only loaded to anything like their capacity for a few hours a day, and anything that can be done to encourage a domestic load which will improve these conditions is well worth exploring. I should like to enumerate a few of the difficulties in the way of bringing these appliances into more popular use. In the first place very few supply authorities have been in the position to supply the necessary power, chiefly because when distribution mains were laid they were only of sufficient capacity for what was considered at that time to be the likely maximum lighting load. Consequently, when heating and cooking supplies are taken from them, it generally means that the voltage suffers very considerably. This has been overcome to some extent by the use of a.c. distribution with rotary converters feeding into the low-tension mains. Another very important drawback to the general use of these appliances is the present high rates for electricity. Until authorities reduce the present charges and institute some system of payment based on rating, or charging at power rates all power used above a certain amount, I feel that there will be very little demand for electricity for domestic purposes. Again, most premises require extra wiring for anything above a 500-watt circuit, and this means a fairly heavy initial expense, i.e. from £10 to £20 for even a comparatively small house. Perhaps some arrangement of free wiring or payment by instalments might overcome this difficulty. We are also rather handicapped in this country as compared with America as regards fittings. The standard bayonet lampholder is not nearly so suitable for power connections as the Edison screw type, which will carry anything up to the capacity of the flexible supplying it. Also, the ordinary tumbler switch is not so good as the American type of rotary switch. It is therefore not safe to use on the majority of lighting circuits in this country, appliances which take more than 3 or 4 amperes. It is now, however, possible to obtain bayonet holders and tumbler switches which are a great improvement on the old ones from a current-carrying point of view, and it would be worth while for supply authorities to encourage the use of these types for any installation where smaller domestic articles, such as kettles, boilers and small radiators are likely to be used. If this were done, it would not be necessary always to install separate circuits and plugs.

[Mr. Gillott's reply to this discussion will be found on page 216.]

North Midland Centre, at Leeds, 19 December, 1922.

Mr. P. Furness: The majority of engineers do not, I think, appreciate the domestic side of electricity supply. One of our chief engineers in Yorkshire recently told me that he was very much afraid of accepting domestic load at the present time in view of the fact that the cables in many of the outer districts were on the small side. It appears to me that this paper will do much to dispel such fears. Is the figure of 300 units per kilowatt of lighting installed obtained from a middle-class dwelling? It appears to me to be rather high; I should have thought that 240 units per kilowatt would have been a good average. I agree with the author's opinion that once a consumer is satisfied he tells his friends. In one of our districts where we induced a number of consumers to adopt the residential or two-part tariff this has occurred, with the result that we have now got some 50 per cent of the domestic consumers on that rate. With regard to the question of installing electric heating, cooking and domestic apparatus, I think that the great disadvantage at the present time from the point of view the medium-class customer is the cost, and the only of getting this apparatus installed is by some form of hire-purchase. For instance, a consumer is not likely to pay £40 for a washing machine. In our district many people are desirous of putting in all forms of electric heating, cooking and domestic apparatus, and if cheap hire-purchase were available they would do so.

Mr. H. G. Fraser: I should like to know if the author has any curves applicable to a residential district. Those given in the paper were of working-class housing schemes, and there would probably be a distinct difference between the two sets. Mr. Furness has said that cables were one of the difficulties in the way of cooking and heating. This is to a certain extent true, although I do not think that one worries much about it. I think the chief drawback in the West Riding of Yorkshire is the difficulty in getting the consumer to buy the necessary apparatus. Even when he has got the apparatus he is very chary about paying for current unless he can get it at a cheap rate. One would imagine that 1½d. per unit is a fairly reasonable rate for cooking and heating, yet it is not easy to sell a large amount of current at that price. I should like to hear other people's experience in this connection. If one could get a reasonable hire-purchase

system, combined with a good showroom, one might even get over the difficulty of the unit price, but in a great many municipal undertakings there are difficulties in the way. A large number of us have no selling powers, which is a great drawback, and we also have no wiring powers. I think that if one could go to a consumer and say: "We will put this in for you, we will let you have it on a reasonable hire-purchase system, and we will fit it up, wire it, and send someone to look after it every now and again," one would have a good prospect of doing business, but I do not think that it is sufficient for the consumer to be left to buy the article with as much assistance as possible. In addition, there will, I think, be a great difficulty in selling electricity for cooking purposes unless there is a good hire or hire-purchase system in existence, and unless the undertaker has full powers to carry out the installation and help the consumer throughout.

Mr. R. E. Gamlen: I think that in a new district one of the chief questions which people ask is: "How does cooking by electricity compare with gas cooking?" Then they ask: "What shall we have to pay for a gas cooker?" In some places I believe that the gas company will lend a gas cooker free of charge if the consumer agrees to use gas, and when a consumer is told that a charge will be made for an electric cooker he is not pleased. A certain amount of argument is needed before he can be persuaded to see the benefits that accrue from their use. The housewife is easy to deal with, but it is the husband who will decide on the question of cost. Another difficulty is that most people are fairly house-proud, and they feel that the house will be damaged during the installation of the wiring. It is necessary, of course, to tell them that the new system of wiring need not cause any damage. I think that that applies particularly in Yorkshire. Again, if people do not own their house they ask the undertaker to consult the landlord. The landlord refuses to have the wiring done and a deadlock ensues. A good argument to use is to point out that, if they wire their premises, in two years they will probably get their money back, due to the economies to be gained. They have extraordinary ideas of the expense, and have always been told that the cost of wiring is excessive. This is due to the fact that there is no great propaganda in some districts. I think that the best way to get people interested is by means of articles in the newspapers, when small points can be explained. Make a few suggestions as to lighting, the places to put lights, and the kind of lights to use. In regard to the question of heating, people do not appear to like an electrical heater in a sitting room. They realize that it is useful in a bedroom or the bathroom, but they like to have a fire which they can poke. I think that the appliances which sell best are irons and small grills. People can generally be persuaded to use a grill, but it is the oven that is the difficulty. A vacuum cleaner, although its usefulness is realized, remains too expensive for the majority. If one could be supplied on the hire-purchase system, or if three or four people were to club together and hire it out, it would be a good plan. The best way to deal with the actual consumer is to try to make an appointment, as he can then choose his time. As to shops, they can be entered at any time, and if the shopkeeper is told that his neighbour has decided to use electricity, he will probably want a supply immediately. It would be a good plan to install in a showroom an ammeter calibrated in pence per hour, so that it can be switched on for exhibition purposes. People will then see what the appliance will cost them.

Mr. W. A. Toppin: I am very much in favour of an annual electrical heating and cooking exhibition in any town of importance. When an industry is developing, the more the actual manufacturer is brought into contact with the actual user the better. Without an exhibition how is this to be done? Exhibitions are good advertisements and acquaint electrical engineers in a town with the latest developments. With regard to the curves shown in the paper, I should like the author to say whether electricity was used to the absolute exclusion of coal or gas, for if coal fires were used the load curves might be higher in the summer time owing to the whole of the cooking and heating being done by electricity. If the summer load were higher, then it would be a further argument in favour of supply authorities encouraging this load.

Mr. S. E. Hall: Not being directly interested in the supply service, I approach this matter from probably a somewhat different angle. I think that a great deal too much stress is laid on the question of price rather than prejudice, because in my experience the lady in the home is essentially a conservative being, especially in house matters. I take it that the curves in the paper are in connection with houses where there was only electricity available for cooking. I raise that point because I am wondering if the ladies in the houses had the opportunity of using gas or a fire as an alternative. My experience is that the present-day lady who has the latest means available, say electricity, will often use gas, or if she has gas will still use a coal fire. That is prejudice which will have to be overcome. The author says on page 201 that the ladies will "make it their business to persuade their husbands to complete the transaction," but my experience is that it is often the husbands who have to persuade the ladies. I would suggest that either the companies themselves or some syndicate, or some company formed by the contractors should install these appliances in various houses free of charge for a year's trial, without any liability whatever, and of course they will have to follow them up and see that they are used. Sales are not effected very often at the time the canvasser calls. It is the housewife who will get these electrical appliances advertised after she has used them and discussed them with her neighbours. That is when the sales will be effected.

Mr. W. B. Woodhouse: The difficulties in the way of developing the domestic load appear to be those which Mr. Furness and Mr. Fraser have pointed out. First of all, it seems necessary that the supply authorities should as far as possible adopt a two-part tariff and make a special effort to get people to use it. The cost of wiring the houses and the first cost of the apparatus are, as far as I can judge, the biggest difficulties in the way. The author has given figures for the village of 282 kW installed and 31 kW demand on the station;

I should like to know the maximum demand for each consumer. As to the benefits of domestic electrical devices, I think that anyone who has used them must appreciate the tremendous saving in domestic labour, and consequently the very great saving in the cost of housekeeping, to which they lead. The paper has helped us to appreciate what a very great field there is for development.

The Author's Reply to the Discussions at London, Newcastle, Liverpool and Leeds.

Mr. W. A. Gillott (*in reply*): I should first thank those who have taken part in the discussions on the paper, for the valuable help and suggestions given. The manner in which the subject has been received at the various Centres proves conclusively the desire of electrical engineers to give the question of domestic load-building much closer study than it has heretofore received. In view of the large number of speakers, I propose to reply to their contributions to the discussion under various headings, instead of individually, as many similar points have been raised by different speakers. By grouping the replies in this manner it enables a more complete answer to be given as a whole. The subjects of tariffs, load curves, distribution and the question as to whether the domestic load is profitable, created the widest discussion, and as these items are so closely bound together I propose to reply to them under one heading.

Tariffs, load curves, distribution and profitable demand.—Many speakers have referred to the question of the two-part tariff and have variously suggested that the fixed charge should be assessed upon the rateable value, the rental value, the floor area, the number of rooms, the lighting kW installed, and the maximum-demand system. It would be difficult for me to give a definite reply to these questions, as they are governed so much by local conditions. In some districts where the area of supply is under one rating committee, it may be advantageous to apply the rateable value system, but should it happen that properties of similar size are rated at different values, owing to the districts depreciating or appreciating, it will be difficult to substantiate a difference in the fixed charge where the lighting installations are similar. This may to a certain extent be overcome by a careful system of grading, but it is well known that this difficulty exists in many towns. To apply this system when the undertaking covers a large area—both town and country—would involve many complications in grading. In stable districts, however, this system has much to commend it, as it is a simple basis. Similar remarks apply to the rental system.

The basis of floor area and number of rooms is also definite or stable. Great care is, however, necessary to adjust the amount of floor area to be assessed, as it is open to considerable compromise unless some definite amount, or the number of watts per 100 sq. ft., is established. One consumer's view in regard to adequate illumination will differ from another's. This may to a certain extent be eliminated by omitting landings, lavatories, passages, etc., and I believe that this is practised in some districts.

To assess a fixed charge upon the number of rooms requires a good deal of careful consideration, owing to the wide variation in their sizes. In the better-class districts it will be quite usual to find the large reception rooms with as many as 10 to 20 lamps installed, yet in the same house other rooms may have but one lamp, therefore the necessity arises of grading the rooms. Either of these methods demands a careful survey of the house before the fixed charge is determined, and such surveys are likely to become costly to the undertaking. Once secured, however, they are permanent as long as the property remains the same.

By basing the fixed charge upon the lighting kW installed a nearer approach to the ideal, from a technical aspect, is secured. If a certain margin is allowed when deciding the amount per kW needed to cover capital and other charges, the changing of one or two lamps of a higher capacity will not be a serious item, as the total will be affected to only a very small extent. It must not be overlooked that the available statistics show that 99 per cent of the British public are honest, and the risk of a consumer changing the majority of his lamps after assessment is very small indeed. To check the consumer's installation is no doubt desirable; this can, however, be quite conveniently and cheaply effected when the meters are periodically changed for recalibration.

The maximum-demand system is perhaps the soundest method from the undertaking's point of view, as it automatically regulates the consumer's fixed charge according to his demand. Its greatest difficulty lies in the task of explaining it in a simple manner to the consumer; also, the cost of a demand indicator is an additional item.

The system of charging upon the lampholder basis deserves consideration, as it has the advantage of charging a consumer upon his individual taste or requirements. In establishing this system it should be a condition that electricity is used exclusively for lighting purposes, and a figure that will permit the assessment being based upon a percentage only of the total number of lampholders installed should be determined. For example, if it is found on investigation that the figure necessary to cover capital and other charges is 6s. 9d. per annum per lampholder installed, it is a wise policy to quote 9s. per lampholder per annum upon 75 per cent only of the total number of lampholders installed. This is a good selling point and overcomes the objection of a consumer who is unwilling to pay the same for his lampholder in a cupboard, which is used perhaps a few hours a year, as for his lamp in the rooms in constant use. This method is in operation in Newcastle and Leicester and a similar scheme is adopted in Hackney, but here the fixed charge is based upon a 60-watt lamp. This is a satisfactory system, its principle being to cover the consumer's normal lighting costs by the fixed charge, so that when a low unit charge is added his lighting account is approximately the same as under the flat rate.

The fixed charge also ensures that the undertaking's capital costs are safeguarded, irrespective of whether energy is used throughout the year or not—a sound business policy. From a technical aspect it is immaterial how the fixed charge is assessed, so long as it bears some definite relation to the undertaking's standing charges necessary to cover a lighting supply; this, of course, is a fundamental fact.

The system of charging suggested by Mr. Robinson and Mr. Berry is sound in principle, its object being to induce the consumer to increase his consumption per kW demand by transferring his load to various operations and so produce a high load factor. A similar system to this is, I believe, in operation in Norway, with satisfactory results.

Certain speakers have expressed the need of a 100 per cent load factor at the consumer's premises to justify a low rate. I am of the opinion that if every domestic consumer offered such a demand it would not be a satisfactory condition for the station, as such demand would appear upon the industrial and the lighting peaks and would to a certain degree defeat its object. If really low rates are necessary, they can be effected by encouraging the consumer to use energy during off-peak hours, e.g. during the night, for water heating, etc. A fixed sum per kW per annum can be quoted, a time switch being arranged to operate at determined times to cut out or in as decided. Such a scheme would tend to improve the general load factor of the station, which is of course desirable.

The figure quoted of 300 units per kW of lighting installed has been criticized as being high. Before this figure was decided upon, some 5 000 domestic consumers' accounts, covering different parts of the country, were investigated in order to obtain average results. Such investigations were further subdivided into three sections, viz. (1) Good-class houses; (2) medium-class houses; and (3) artisans' dwellings—using mainly slot meters—and the average annual consumption per kW of lighting installed was found to be, under the various headings: (1) 348 units; (2) 309 units; and (3) 248 units. With such returns the estimated consumption of 300 units per kW of lighting installed is justified. It must be realized that this figure is submitted as a guide to the average return expected, and naturally does not make special provision for "freak" installations. I agree with Mr. Robinson that an ideal tariff is reached by the slow process of evolution, and until we reach that ideal we must work upon sound business averages.

The curves in connection with the Billingham village, no doubt owing to the fact that these are the first set made public, have created considerable interest and prove in no uncertain degree that the domestic cooking and heating load does not present quite so many plant and cable difficulties as most engineers considered. Naturally the low rate offered encourages a wider use of electricity and, as the Billingham load curves indicate, a long-hour use is made, but it must be realized that these tenants do not enjoy a *very* low rate, and that upon the whole they are careful people and do not unnecessarily waste the energy.

In comparing the returns with those of two other housing estates it is of interest to relate that the load-curve characteristic is similar. In one instance where approximately 950 kW of cooking, heating, wash boilers and lighting is installed, the maximum demand was 8 per cent, and the average maximum demand 5 per cent of the total connected load of the village. In the other instance where 1 980 kW of cooking, irons and lighting is installed upon the whole estate, the maximum demand, which also occurs on Sunday, is 100 kW, i.e. approximately 5 per cent. It will be noted that in the cases of Billingham and the 950-kW estate, where each house has a "mixed" load, i.e. cooking, heating, wash boiler and lighting, the percentage maximum demand—10 per cent and 8 per cent, respectively—is higher than that of the third estate, which is only 5 per cent. In the latter case no heating or wash boilers are installed, but it is found upon investigation that although the percentage of demand varies, the return per kW of maximum demand on the station plant is practically identical, i.e. approximately 3 000 units per annum per kW of maximum demand. This must be regarded as a satisfactory figure and one which justifies a comparatively low rate, and it should encourage authorities to seek the load.

Several speakers have asked how the Billingham curves compare with those of better-class residential districts. Unfortunately, at the moment I am unable to submit a curve of this nature, but I hope to do so later. The curves given in my previous paper * represent the return of 13 houses, cooking only, the rateable value of the houses varying from £25 to £60 (pre-war values).

In reply to Mr. Woodhouse, the individual consumer's maximum demand at Billingham varies somewhat, and I have no definite records of all the houses. I understand, however, that it is from 3 to 5 kW.

The question has been raised as to the effect of a general cooking and heating load in a residential district upon a network originally laid for lighting. It is difficult to answer this question accurately, as so much depends upon local conditions. If the cables were laid without much thought for the future it will probably be found necessary to reinforce the network, or it may be possible, as I have found in certain cases (and these can only be decided upon on the spot), to connect quite an appreciable cooking load to a lighting network, owing to the fact of the load being an off-peak load of high diversity. In the case of outlying districts on a d.c. supply, it will probably be found necessary to make some provision for increasing the cable capacity.

The automatic substation mentioned by Mr. Dickinson is a bold experiment, and one which will be watched with interest. The class of district will determine, to a large extent, whether the expense of such a substation is justified. As many speakers have remarked, however, and as the curves prove, the domestic load is a profitable one, can be developed to almost any proportion, and justifies certain expenditure.

With such undertakings as Mr. Rye mentions quite a considerable revenue can be secured by the use of small appliances. These do not affect the cables but, as Mr. Rye points out, they improve the financial results.

Hire of appliances.—Reference has been made to

* *Journal I.E.E.*, 1915, vol. 53, p. 42.

the possibility of assisting consumers to use electrical energy by establishing a hiring policy. If any real business is to be done, it is necessary to offer certain appliances upon hire. Places such as Glasgow, Newcastle, Marylebone, Hackney, etc., have proved that the hiring of cookers, for instance, is quite satisfactory. All undertakings now have the power to hire apparatus and it rests entirely with them as to whether they exercise that right. With cooking circuits there does not appear to be any reason why the wiring should not be hired also. This can be run in C.T.S. or similar cable, and is easily removed if necessary. Generally speaking, if ½d. per unit is added, cookers complete with the wiring can be hired without the necessity of a separate hire charge. It is usual, however, for the consumer to pay the cost of wiring and, so long as he is willing to do so, the question of hired cooker wiring does not arise, except in cases of small property which is supplied through a slot meter, so that all charges can be consolidated, as in Hackney, Woolwich, Leicester, etc.

I would repeat that the supplying of appliances on hire increases the sale of energy. Further, such a transaction with a consumer enables the undertaking to keep in close touch with the installation and this constitutes one of the links of service to the consumer.

Co-operation in the industry.—This subject has been raised by many speakers and is of vital importance to the progress of the industry. There are many points of view and I could not effectively deal with them here. Generally speaking, there is a desire for concerted action, and in many centres there are good results, due to a clear, mutual understanding. I am of the opinion that if all parties were to realize thoroughly the fact that the great buying public is, after all, the deciding factor, much good will accrue. The great game of business building is most fascinating and by agreeing upon a definite plan of progress the advantages will be mutual. Each party will, no doubt, secure a greater return by co-operation than by individual action.

Commercial activity.—Reference has been made to the extent of an undertaking's activities in regard to propaganda work, i.e. as to whether it should embark upon an extensive scale or proceed in steps. When some new decision is arrived at, such as a reduction in the tariff or the establishment of a hiring policy, I think that such notice should be given a wide publicity either through the local Press or by letter to the consumer. The backs of the account form should, however, certainly be used to convey a suitable message. By making a public announcement the attention of non-consumers is secured and, further, the establishment of a showroom with properly conducted demonstrations will not only attract new consumers but interest the old to make wider use of electricity.

I believe in the principle of spending small sums and often when dealing with one town, and not attempting to interest too many people at once, otherwise proper attention may not be given to inquiries. As Mr. Berry said, it is one thing to have a commodity available, but the most important thing is to present your proposition to the consumer in the right way, and in this respect the representative must be a qualified person, suitably trained in salesmanship. Mr. Muncaster was correct in saying that such work must not be done by an odd man who may have a certain amount of spare time. Electrical undertakings have a valuable commodity to sell and its disposal should be in the hands of good and well-paid men; it is the cheapest way to get the desired result.

It has been stated that by offering units at a low rate it is not necessary to advertise, as the cheap units will "sell themselves." I cannot agree with this view: it is essential that consumers and prospective consumers must be shown what electricity can do for them, and if the various applications are not brought to their notice, how can one expect them to use electricity? It may be true that they have some knowledge of the uses of electricity, or where the undertaking is situated, but unless the "desire to use" has been established in their minds very little progress will be made. The old saying "Good wine needs no bush" is no slogan for the present-day business man.

Miscellaneous.—Mr. Thorrowgood has remarked upon Mr. Berry's figure of £72 per annum for electricity. Mr. Berry did not intend to convey the idea that this was the figure for the usual house, but quoted it only as an illustration; there are, of course, many households in which much more than this is spent on lighting, cooking and heating, but upon an average 3 000 units is consumed per annum for all purposes in the average middle-class house of six persons. Using, perhaps, one coal fire, the cost may be anything from £15 to £25 a year. When it is realized that many workmen in humble circumstances are using electricity for all purposes through a slot meter at a cost of from £8 to £12 per annum, it will be appreciated that electricity is not a luxury but a necessity.

I agree with Mr. Baker that the key to progress is economy, but surely electricity offers this. His comparison of the heat units in the coal heap at the electricity works with those in the coal in the householder's range is but one side of the question. In a recent report on "Solid Fuel Ranges" by Professor Barker—a series of careful tests carried out for the Government—it is shown that the kitchen range of good design usefully employs 2 per cent only of the total heat units delivered to it! It has also been proved that between 70 and 80 per cent of the coal used in a house is consumed in the kitchen range. Now, from an average of some thousands of instances, a middle-class household of six persons using electricity exclusively for cooking, the consumption works out at 40 units per week. The rates of supply differ in many districts, and when making recommendation to a householder one must be governed by local conditions. It is not suggested that where the rates are 2d. per unit and upwards it is cheaper in comparison with coal at, say, 45s. per ton, but where a supply is offered at about 1d. per unit—which is now the case in many districts—one can safely advise the use of electricity for cooking and heating.

Mr. Baker's communicated remarks to a large degree modify his first criticism. The whole object of the paper was to attempt to indicate in a small measure the field open to the supply authority and to point out how the domestic load could be dealt with. His three points

are being seriously handled by undertakings generally, especially the first two. The hiring proposition is again being considered, and each week sees an additional authority agreeing to hire appliances.

Mr. Cross requires an explanation of the figure of 300 units per annum per kW installed for cooking, in comparison with the consumption of 1 unit per person per day. In the first case the figure is quoted to the engineer designing tariffs as an estimated figure to expect where a cooker is installed and in normal use. It is perhaps a little low, but it is on the safe side from his point of view. In the second case it is the figure often quoted to the consumer as his approximate cost for cooking when all meals are provided electrically and the appliances are suitable in size to his needs.

The question of converting a kitchen range boiler to electricity is dealt with by heating the water at the cylinder or hot-water storage tank. I believe that there are several of these in use in Newcastle, and no doubt the electric supply company would gladly give Mr. Cross details if he inquired. Almost every maker of cooking and heating appliances will provide a list illustrating these devices.

Mr. Muncaster asks if the quarterly account is a suitable time for introducing new avenues of use. I certainly see no reason why this should not be the case; the backs of the account forms often carry an advertisement suggesting the further use of electricity. The mere fact that the consumer will be forwarding his cheque suggests that he might inquire for something which he saw in the leaflet.

One undertaking which enforced a minimum payment for lighting had difficulty in satisfying consumers as to the reason of such minimum payment. It decided to send suitable leaflets with the accounts, showing how kettles, toasters, etc., could be used from the lamp-holders. The result was excellent, and they now have but few consumers who use so little energy that the minimum payment is enforced.

Mr. Carter's case is one of the very few where the consumption for lighting is much below normal, i.e. if his load *is* 1 kW. If his total fuel and lighting bill is £20 per annum and he is careful in the use of coal, I am of the opinion that his account would be quite acceptable to him; he is living in a district where electricity is cheap and appliances can be hired at moderate rentals, and I suggest that he, being an electrical engineer, might try electricity for other purposes than lighting. The cost of the specific operations which he mentions will be gladly given by the supply company. It was not the intention of the paper to give such details but to interest the electrical undertakings in the hope that they would do so.

Mr. Dickinson asks for an explanation of the apparent discrepancy between the figure given on page 197 of 3 240 units per kW and the figures on page 200 of 290 000 units per annum. The first set of figures relates to the result of a study of 13 consumers using cookers in private houses; the figure of 3 240 units represents the consumption per annum per kW of demand that falls upon the system peak, whereas the figures on page 200 refer to the consumption for cooking at four restaurant and canteen kitchens, i.e. commercial use, an entirely different proposition. These cases were quoted to indicate that both the domestic and commercial cooking load are worth cultivating.

Mr. Waygood has evidently misunderstood the reference to the suggested rentals. The paper is offered to electric supply authorities with certain suggestions and the statement of 20 per cent per annum upon the *net cost* as a suggested rental of cookers is quite a different matter from the 20 per cent of Mr. Waygood's *list price*. One is the wholesale price which the authority would pay, and the other is the price which the consumer would pay if he bought at a retail shop. The £22 cooker referred to is hired by many authorities at 10s. per quarter, inclusive of all maintenance, and in some districts as low as 5s. per quarter. My figures were quoted as a sound basis to cover interest, capital redemption and maintenance. He also refers to the consumer being misled as to the cost of units; here also is a misunderstanding. The paper distinctly says that he is to pay a fixed charge plus $1\frac{1}{2}$d. per unit, and on this basis his normal lighting account will be practically equivalent. It is the extra units that are costing him $1\frac{1}{2}$d. only, and $1\frac{1}{2}$d. is not the average cost per unit. The various other matters which Mr. Waygood mentions are interesting, but I do not agree with all his conclusions, and as they do not come within the scope of the paper I must ask to be excused from dealing with them.

THE POSSIBILITIES OF TRANSMISSION BY UNDERGROUND CABLES AT 100 000/150 000 VOLTS.

By A. M. TAYLOR, Member.

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SUMMARY.

The paper is primarily a plea for the use of single-phase cables. The effect of separating the cores is considered, both in its relation to easing the potential gradient and in relation to eddy currents induced in the lead sheathing.

The gain effected by employing "intersheaths" is pointed out, and the author's proposals for obviating the disadvantages of intersheaths by combining their employment with a six-phase transmission are considered.

An actual transmission of 50 000 kW at 100 000 volts over a distance of 30 miles is worked out in detail and compared with a similar transmission at 30 000 volts. A saving of roughly £500 000 is shown.

The principal conclusions arrived at are:—

(1) Reliability under the six-phase/three-phase system very greatly increased, as compared with plain single-core cables (as at Gennevilliers), or with three-phase cables for equal voltage.

(2) The author's arrangements will permit of loads of poor power factor being taken up, with positive gain in efficiency and regulation.

(3) The maximum voltage gradient being no greater with 100 000 volts than with 30 000 volts, such transmissions can be undertaken immediately the cable makers are in a position to guarantee the cables.

(4) The investment in capital outlay proceeds, in the six-phase/three-phase scheme, in proportion to the development of the load. A start could thus be made with only 8 000 kW.

(5) The reduction in line-charging current in the six-phase/three-phase scheme, and the improvement in "regulation" are very considerable, as compared with those for any other proposals.

TABLE OF CONTENTS.

I. INTRODUCTION.

The efficient and cheap transmission of power electrically over long distances is at present one of the most vital problems connected with the distribution of electricity. The object of the present paper is to consider how this may be carried out in those cases where the use of overhead wires at high voltages (e.g. 100 000 to 150 000 volts) is not considered to be advisable. Doubtless there will be large areas over which the employment of overhead transmission will be permissible, but, on the other hand, the use of duplicate lines of tall towers at comparatively frequent intervals, with spans of heavy cable liable to be brought down during severe snowstorms or other atmospheric disturbances (or liable to malicious interference), could hardly be faced in the vicinity of large towns. There is, moreover, always the possibility that, if underground cables could be employed at voltages of the same order as that of overhead lines, it might be possible to obtain wayleaves over great distances along the existing trunk lines of railways, and in such a case the cost of transmission might be reduced to a figure as low even as that with overhead lines.

II. LIMITATIONS TO THE USE OF THREE-CORE CABLES.

The limitations to the use of three-core non-concentric cables are well known, but it may be stated that directly the pressure is raised to 100 000 volts it becomes almost impossible to get the depth of insulation which is needed, both between core and core and between core and earth, within the overall limiting diameter of the lead envelope, which should not appreciably exceed 4 inches.

The recognition of the difficulties thus obtaining in three-core cables has caused many minds to turn to the possibilities of using three single-core cables for three-phase transmission, and such a scheme was proposed by Mr. C. J. Beaver in a paper* read before the Institution in 1914, and has more recently been very fully worked out in a preliminary way by Messrs. Clark and Shanklin of America and presented in the form of a paper before the American Institute of Electrical Engineers.†

From the data given by Clark and Shanklin it is easy to deduce that, with a pressure of 100 000 volts and a frequency of 50 periods, and with unarmoured cables, the lead sheathing being continuously earthed and the cables being not further than 6 inches apart from one another, the loss due to eddy currents in the lead, in a cable of the dimensions shown in Fig. 1, will

* *Journal I.E.E.*, 1915, vol. 53, p. 57.

† *Journal of the American Institute of Electrical Engineers*, 1919, vol. 38, pt. 1, p. 917.

not exceed 10 per cent of the I^2R loss in the copper alone.

With a 5 per cent copper loss the total loss with unarmoured cables would therefore be increased only from 5 per cent to 5·5 per cent of the total power, i.e. an addition of 0·5 per cent.

It may therefore be taken that, provided single-core cables can be constructed to withstand a pressure of 57 700 volts to earth, both in the cable itself and at the joints, it is allowable thus to separate the phases. The maximum potential gradient in the cable itself can be kept down to that now obtaining in three-core non-concentric cables (about 40 000 V/cm) by simply constructing the copper core with a hempen centre; but the difficulty of jointing is rather more serious.

The author has developed a system on the separated-phase principle which permits of the pressure between the outermost core and earth being reduced to some 18 000 volts while still obtaining 100 000 volts for transmission, coupled with certain other advantages of moment, and it has been thought that a description of this system would be of interest at the present time. In what follows it is to be understood that the amount

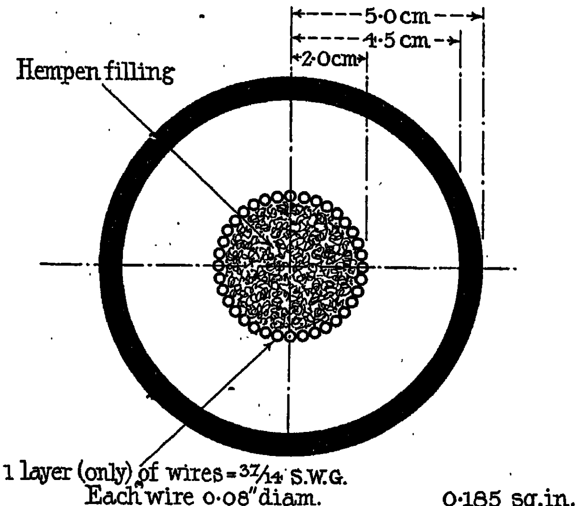

FIG. 1.—Insulation to withstand 57 700 volts to earth.

of power to be transmitted is 50 000 kW, the load factor 40 per cent, and the distance 30 miles.

It is practicable to keep the plain copper voltage-drop (i.e. excluding the lead-sheath loss) over a separated-phase 100 000-volt single-core system down to 2½ per cent of the total power, or 2·75 per cent including lead-sheath loss. On a 30-mile line the lead-sheath loss is thus, at 50 periods, only 0·25 per cent of the total power transmitted.

In Appendix B the author has given certain data with regard to the "cable constants" of a system employing plain single-core unarmoured cables such as shown in Fig. 1 (e.g. capacitance, inductance, resistance, etc.). It may be taken that the figures therein given for the copper voltage-drop, reactance-drop, etc., are not far wrong for the six-phase/three-phase system to be described.

Similarly, the induced current losses in the lead sheathing will also be of the same order, in fact rather less.

It therefore becomes practicable to consider armoured cables, as these might be desirable on long lines laid along railways. By increasing the amount of copper by 10 per cent, the iron-wire loss can probably be compensated for by the reduced copper voltage-drop, and may then be neglected altogether.

In Fig. 2, sections of the various cables experimented on by Clark and Shanklin are given, and also their "Cable C" and, in addition, the cable (marked "No. 11") shown in Fig. 1 of the present paper. The former cable is that on the tests of which the estimated lead-sheath losses herein taken are based.

The sheath diameter of the author's six-phase/three-phase cable is virtually the same as that of the cable shown in Fig. 1. Hence the results for the cable (Cable C) of Fig 2 apply also substantially to the author's

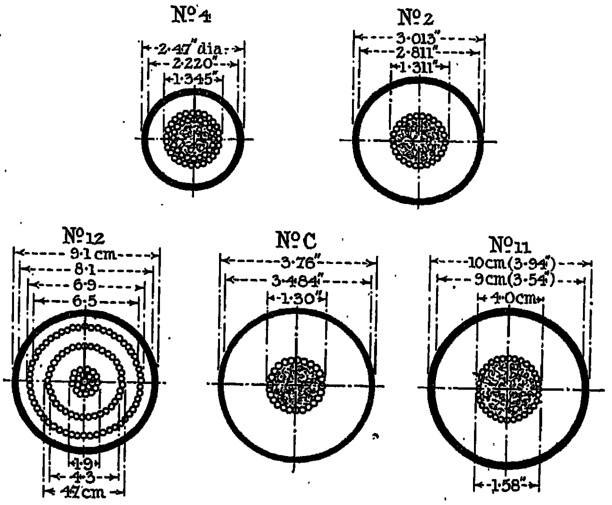

FIG. 2.—Cables experimented on by Clark and Shanklin.

Cable 4: Percentage increase in effective resistance = 14·4 at 25 ∼ and 96 at 60 ∼; area = 0·79 sq. in.
Cable 2: Percentage increase in effective resistance = 8·8 at 25 ∼ and 48 at 60 ∼; area = 0·49 sq. in.
Cable C: Percentage increase in effective resistance = 4·5 at 25 ∼ and 22 at 60 ∼; area = 0·216 sq. in.
Cable 11: Area = 0·185 sq. in.
Cable 12: Cable proposed by the author.

system, the location of the average current with regard to the lead sheathing being virtually the same.

III. The Grading of Cables, and Potential Gradients.

As the author's system depends for its proper appreciation upon the establishing of certain principles, these will first be investigated and afterwards the system itself will be described.

In Fig. 3 is given a curve ABCD representing the potential gradients of a cable having a core of radius 0·65 cm. The voltage gradients are plotted as ordinates, and the different radii of circular concentric sections of the insulation are plotted as abscissæ. The interior radius of the lead sheath is assumed to be 22 cm, and the pressure between the core and the lead sheath is 69 200 volts. The figures given at various points along the curve represent the voltage gradients

at those points. The insulation is assumed to be applied in concentric layers, all of material of equal permittivity. Four such circular sections are shown immediately contiguous to the core, and one section at the extreme circumference. The values 8 750, 7 720, 5 700, 4 030, etc., marked between the dimension lines at the foot of the diagram represent the integration of the areas contained in the different portions of the potential gradient curve, and therefore represent potential differences up to the radius of $2\frac{1}{2}$ cm. To be complete, the diagram should of course show the whole 44 of these circular sections, but for the sake of simplicity the remainder are omitted. Each of the equipotential boundary lines separating these circles may be considered to be a metallic sheath of extreme thinness, merely for the purpose of fixing ideas.

If, now, the capacity per foot between any one intersheath and any other intersheath be worked out by means of the formula

$$C = \frac{C_a \cdot k_{(av.)} 2\pi l}{\log_e (b/a)}$$

where $k_{(av.)}$ = permittivity relative to air = 3·2;
C_a = capacity per cubic centimetre of air
= $0 \cdot 08842 \times 10^{-12}$ farad;
l = length in cm = 30·5;
b = outer radius of insulation in cm;
a = inner radius of insulation in cm;

the following values are found:

$$\left.\begin{array}{l} 0 \cdot 000124 \times 10^{-6} \\ 0 \cdot 0001315 \times 10^{-6} \\ 0 \cdot 000185 \times 10^{-6} \\ 0 \cdot 000238 \times 10^{-6} \\ 0 \cdot 001175 \times 10^{-6} \end{array}\right\} \text{farad per foot,}$$

the last figure being for the centimetre depth immediately below the lead sheath. In a similar manner the currents for these successive sections are calculated from the formula

$$i_d = \frac{2\pi fce}{\sin \theta_d}$$

where f = frequency,
c = capacity per foot length,
e = voltage between core and intersheath,
θ_d = phase angle of dielectric power factor,

giving the following values:

$$\left.\begin{array}{l} 0 \cdot 341 \times 10^{-3} \\ 0 \cdot 319 \times 10^{-3} \\ 0 \cdot 331 \times 10^{-3} \\ 0 \cdot 302 \times 10^{-3} \\ 0 \cdot 321 \times 10^{-3} \end{array}\right\} \text{ampere per foot of conductor.}$$

It will be noted that the current per foot is constant (within the limits of rough approximation), which means that the capacity current is of the same value

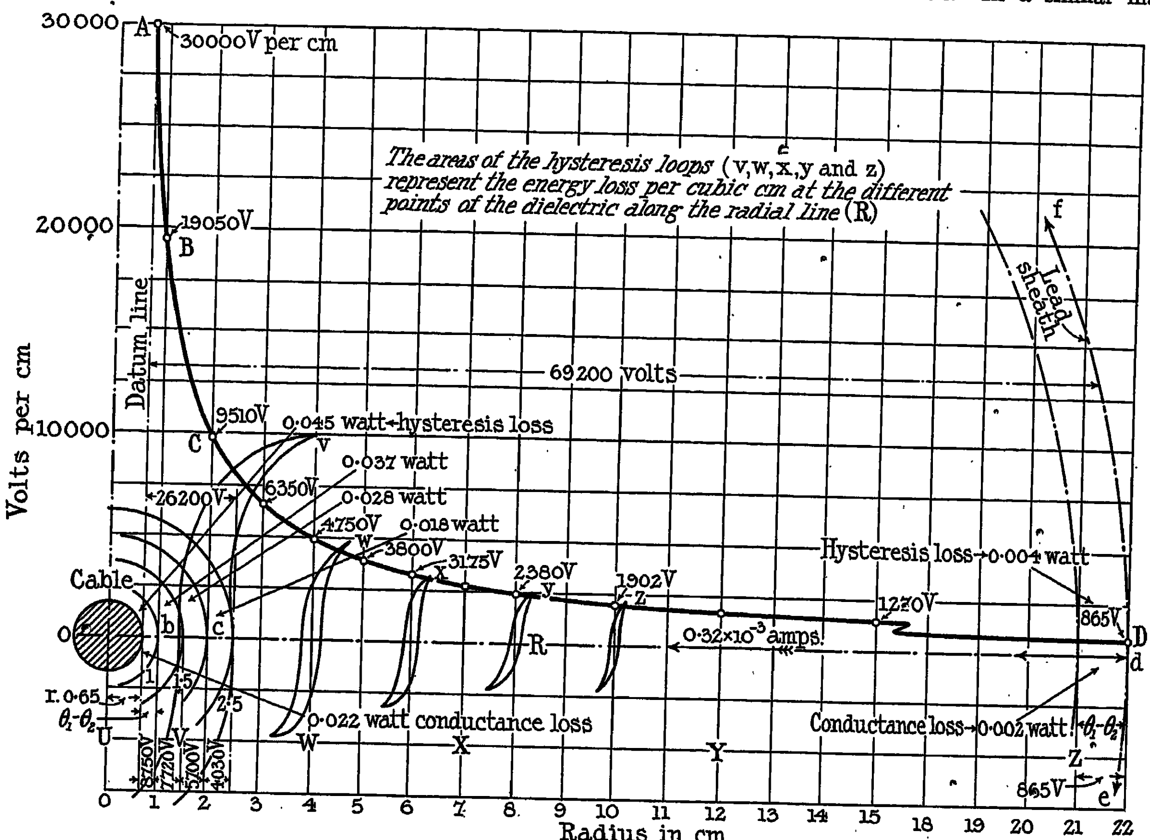

FIG. 3.—Single-core cable; potential gradients at different radii.

in the widely-varying concentric slices of insulation and that the voltage differences across each successive layer vary inversely as the capacity of each layer. Examining the matter further and assuming that the power factor of the dielectric keeps constant throughout the successive layers (which of course is not the case owing to the differing temperatures, but this only makes the author's argument all the stronger), we get the values of the watts lost in each successive layer from the formula

$$w_d = i_d . e . \cos \theta_d$$

which gives us the values shown on Fig. 3, namely

$$\left.\begin{array}{l} 0 \cdot 045 \\ 0 \cdot 037 \\ 0 \cdot 028 \\ 0 \cdot 018 \\ 0 \cdot 004 \end{array}\right\} \text{watt per foot.}$$

If the last-mentioned reading had been taken over a ½ cm difference of radius, instead of 1 cm in conformity with the other readings, it would have had the value of only 0·002 watt, which is less than 1/20th of the value obtaining on the slice of insulation immediately next to the core. Now the volume of the slice immediately contiguous to the core is of the order of 1/40th (per unit length of cable) of that at the extreme circumference, and the amount of heat developed is over 20 times, consequently the heat developed per cubic centimetre is of the order of 800 times that generated in the section at the extreme circumference.

In a similar manner it can be shown that the watt loss due to the purely ohmic insulation resistances of the different sections, and to the true leakage current which passes through them, follows a precisely similar law and is, again, 800 times the heat developed per cubic centimetre. This will be seen at once by a comparison of the formulæ for the elastance and the true resistance, to which also may be added the thermal resistance. The three formulæ are of the following relation, viz.

$$R_g = \text{(Insulation resistance)} = \frac{R_g \text{ (specific)}}{2\pi l} \times \log_e \frac{b}{a}$$

$$S = \text{(Elastance)} = \frac{S \text{ (specific)}}{2\pi l} \times \log_e \frac{b}{a}$$

$$R = \text{(Thermal resistance)} = \frac{R \text{ (specific)}}{2\pi l} \times \log_e \frac{b}{a}.$$

A little consideration will show that in the case of the first two formulæ the voltage differences follow the above-mentioned law and that the temperature differences will also follow an identical law.

The true conductance losses have also been worked out from the first of the above three formulæ, and the initial and the final values shown in Fig. 3 are 0·022 watt and 0·002 watt. In the particular case considered, therefore, the leakage conductance loss is very nearly equal to the dielectric hysteresis loss, the former being based upon a value for the specific resistivity of 150 × 10¹⁰, which is a value found fairly frequently for the lower temperatures in Messrs. Clark and Shanklin's experiments, and the latter being based upon a constant dielectric power factor of 0·015, which also obtains only at the lower temperature values (up to 72° F.). The author is quite satisfied that the power factor, representing partly as it does the energy lost by dielectric hysteresis, plus the true leakage loss, must be much greater in the inner layers of insulation, which are at a much greater temperature than the outer layers; and, as already mentioned, this would still further strengthen his argument.

Conversely, from the third equation we can see that the greater amount of heat liberated in the sections close to the core has enormously greater difficulty in reaching the circumference of the cable. It therefore follows that any method that tends to relieve the potential gradients in the sections next to the core, even if this occur at the expense of the sections nearer to the circumference, is a very potent factor indeed in easing the situation. In Fig. 4 the author has shown the remarkable effect upon the diameter of the cable of introducing metallic intersheaths and forcing these to work at such potential differences between each consecutive pair that the maximum voltage gradient is maintained more or less constant throughout. The result of this is that the whole of the 69 200 volts is absorbed within a radius of 4⅛ cm, though it should be mentioned that the diameter of the core itself, in this particular case, has been somewhat increased (owing to inadvertence), and this unduly magnifies the result.

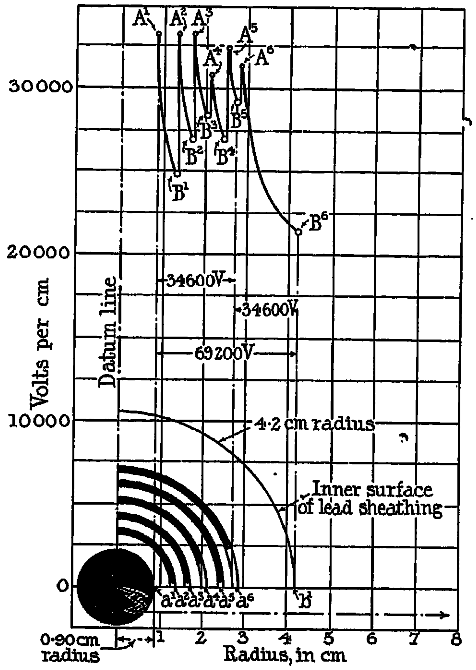

FIG. 4.—Multiple (cylindrical) core cable; potential gradients at the surfaces of the different cores.

A further consideration of Fig. 3 and of the figures given in Appendix C will show that such a result can be obtained only at the expense of having continually increasing capacity currents in successive layers as we work outwards, the current being no longer

constant from the centre to the circumference, and practical arrangements for dealing with this have now to be considered.

INTERSHEATHS.

Fig. 5 may help to fix ideas. This may be considered to be an investigation of what takes place in a single phase of a three-phase system embodying one single-core cable per phase, each such cable having "intersheaths" in accordance with Mr. Beaver's proposals.

The condition considered is that the half-wave of E.M.F. in the secondary is in a downward direction through the secondary winding, "sucking" the principal or "load" current of the central core of the cable and carrying it through to the neutral point of the transformer winding. The various components of the capacity current are shown coming along from the line and finding their way to the central core, as illustrated by the three large arrows 120° apart.

Consider, for instance, the current (f) which arrives through the outermost conducting sheath. Finding a path leading to the tapping of the transformer, the "surplus" current of the outermost section of the

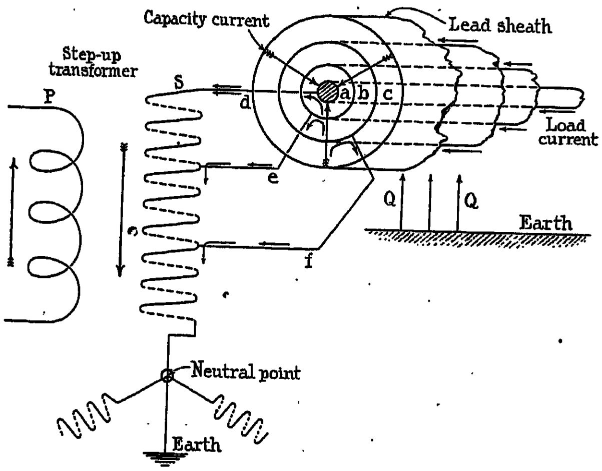

FIG. 5.—Diagram to illustrate the relief of the inner layers (capacity and leakage current) by means of intersheaths.

insulation, instead of going through the successive layers of insulation to the central core and heating up the innermost layer in the way just described, now takes a short cut across to the tapping of the transformer. The "surplus" element of the current (e), which has passed through the insulation from the outermost sheath to the intermediate sheath, similarly takes a short cut across to the corresponding tapping, with the result that the insulation next to the innermost core is called upon to carry only the capacity current (d) due to its own capacity. Referring again to Fig. 4, it will be understood that, if we had chosen, we could have made the section of insulation next to the core work at a less voltage gradient than 38 000 V/cm, and so have eased the situation as regards this section. The author believes that by adopting the principle indicated above the potential gradient on the outermost layers could be raised considerably higher than would be indicated by Fig. 4. For one reason, these layers being close to the lead sheathing would be the coolest in the whole cable and consequently the power factor of the dielectric would be the lowest and the resistivity by far the highest, since this latter varies enormously with the temperature.

In all probability the operation of dielectric hysteresis is very similar to that of magnetic hysteresis, and the loss (i.e. the power factor where the leakage loss is low) is therefore proportional to a function of the potential gradient, and the loss by pure leakage conductance through the dielectric is proportional to the square of the potential gradient, and both of these (and particularly the latter) depend to a very great degree on the temperature obtaining in the dielectric.

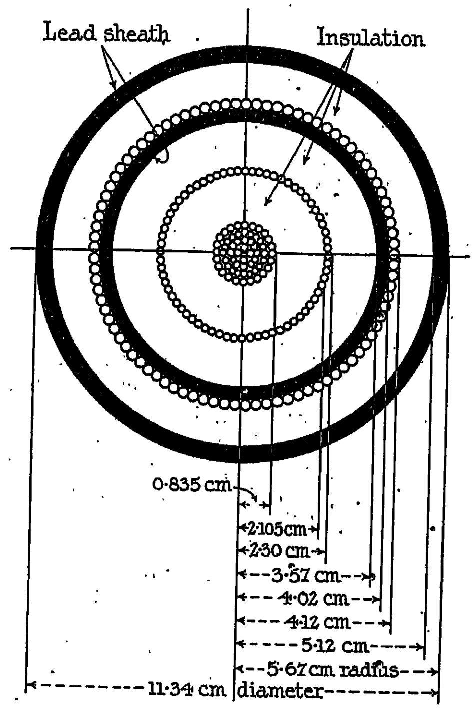

FIG. 6.

The question of the dielectric losses and potential gradients is investigated quantitatively in Appendix C.

IV. DESCRIPTION OF THE OPERATION OF THE SIX-PHASE/THREE-PHASE SYSTEM.

Referring now to the author's six-phase/three-phase system, which will be briefly described in connection with Figs. 7, 8, 9, 10 and 11, attention is invited to a consideration of one—say the top—of the three small six-phase systems or "hexagons" shown in Fig. 11 (which gives the general scheme) and reproduced by itself in the upper part of Fig. 7. This consists of a "bank" of the secondaries of a step-up transformer coupled in "double star" to give voltages which are in six-phase relation, the vector diagram for which is shown in the upper part of Fig. 8 (right-hand side). This bank of transformers is connected to the two

cables shown at the top of Fig. 7, these cables being shown more in detail in Fig. 6.

It will be clear that, if the upper "hexagon" shown at the right-hand side of Fig. 8 be earthed (as shown) at a point having a potential not far different from

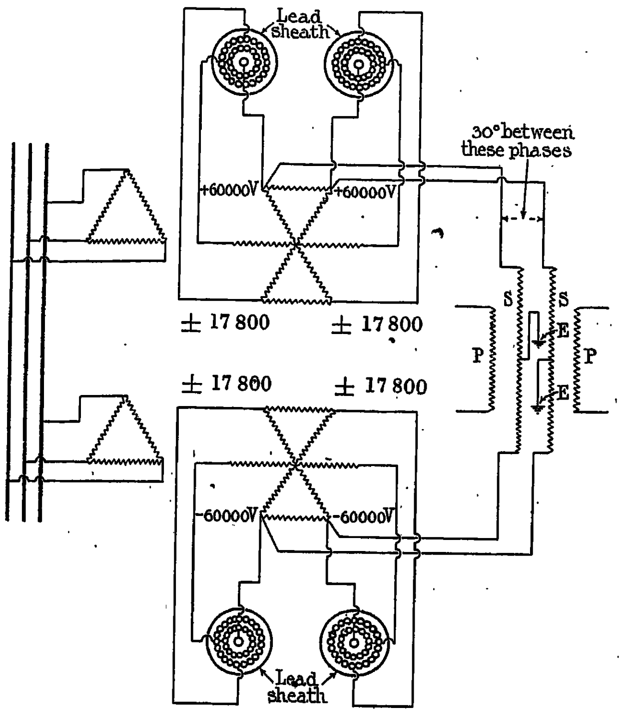

Fig. 7.

that of a point midway between the points "e" and "f," instead of at the "natural" neutral point of the hexagon, the potentials of the remaining corners of the "hexagon" with respect to earth will be given by

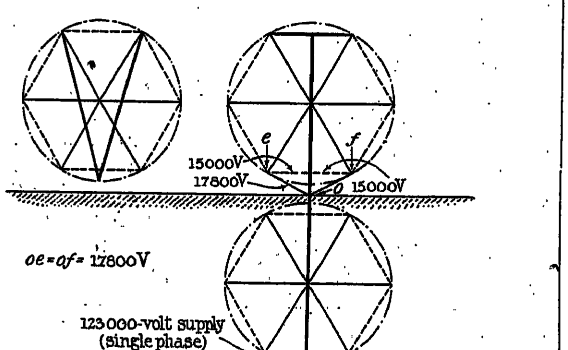

Fig. 8.—Arrangement of combined six-phase and single-phase supply (for railways).

vectors connecting these corners with the said earthed point.

These vectors are not shown in the right-hand top diagram of Fig. 8, but vectors from the two topmost corners to earth are shown in that figure in the left-hand top diagram, in heavy lines, and the positions of the other vectors can easily be obtained.

Both in Figs. 7 and 8 are shown, in the lower half of each figure, arrangements the inverse of those in the upper half, and to the right of the former figure there are shown two single-phase transformers (which may be called the "principal" or "major" transformers) and these are each connected across the points marked "+ 60 000 V" and "− 60 000 V." The secondary of each of these principal transformers is wound for 120 000 volts, and its mid-point is earthed. It may help towards a more ready understanding if these two "major" transformers are replaced, as shown vectorially in Fig. 8, by a single transformer, connected to the two "hexagons," at extreme top and bottom, at points

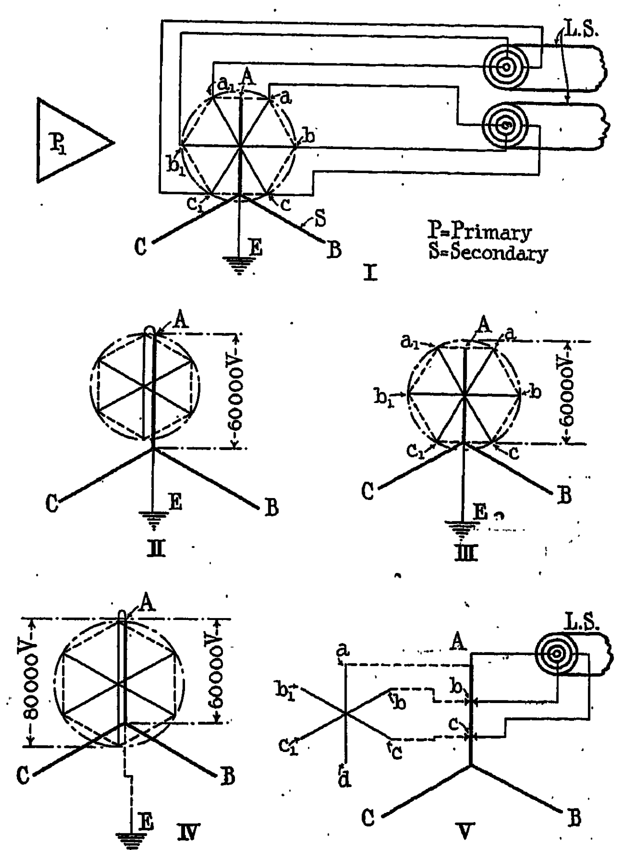

Fig. 9.—In cases I, II, III and IV, hexagons will also be similarly carried by (B) and (C) and two other pairs of concentric cables.

midway between each top and bottom pair of corners of the said "hexagons."

It is demonstrable that, if neither of the two six-phase systems be at any point connected to earth, the potentials of the lower corners of the upper "hexagon," and of the upper corners of the lower "hexagon," will take up the values shown more precisely by the vector diagram in Fig. 8, receiving their potentials from the "major" transformer, through the connections at the extreme top and bottom of the two "hexagons." In this diagram each chord of the hexagon represents 30 000 volts, and this is the voltage obtaining between the innermost core of each cable and the intermediate

core, and between the intermediate and outer cores. The voltage between the outer core and the lead sheathing is shown to be only 17 800 volts (if desired, only 15 000).

The cable shown in section in Fig. 6 has been so designed that the maximum voltage gradient on the innermost core under these voltages will not exceed about 38 000 V/cm, i.e. the potential gradient at which three-phase three-core non-concentric cables work at the present day. On the middle and outermost cores it will be 29 000 V/cm and 20 000 V/cm, respectively.

Since the capacitance increases as we work outwards, and since it becomes very desirable (in the case of failure of the lead sheathing or of the outermost insulation) to have as low a voltage as practicable between the outermost conductor and the sheathing—for reasons which will appear later—it will be evident from an inspection of Fig. 8 that the arrangement of the six-phase "hexagons" in the manner shown in Figs. 7 and 8 affords a very nearly ideal way of distributing the potentials.

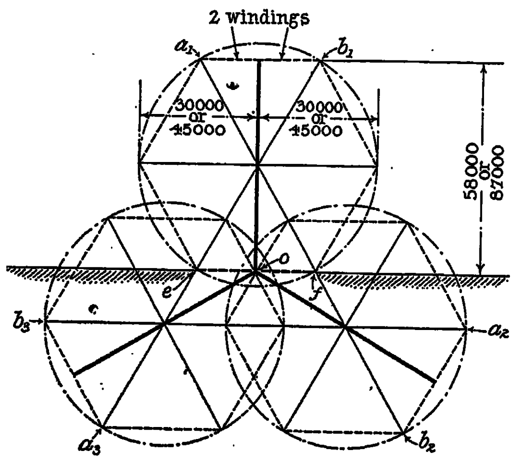

FIG. 10.—Arrangement for minimum stress between outermost core and earth. (*Note:* 58 000 × $\sqrt{3}$ = 101 000, and 87 000 × $\sqrt{3}$ = 150 000.)

Let us now consider Fig. 10. In this case the lower "hexagon" of Fig. 8 is replaced by two "hexagons," and the single-phase "principal" transformer (or its equivalent as in Fig. 7) by a three-phase "principal" or "major" transformer system, the neutral point of which is earthed.

In Fig. 9 are shown various connections of transformers forming the "hexagons," or six-phase systems, to be used in conjunction with the main three-phase system (or "major star"), the transformer windings being represented by thick lines. In Fig. 9 (I) there is shown a single "hexagon," connected to two cables. The "hexagon" will be repeated on each of the arms B and C of the "major star," as may be seen in detail in the parallel case of Fig. 11, which represents, extended to all three phases, the details—shown for one phase only—of Fig. 9 (I).

In the cases of Fig. 9 (II and IV) the current from the bottom corner of the "hexagon" must be carried by a separate small cable.

The vector diagram for Fig. 9 (I) is given in detail in Fig. 10. The corners a_1, a_2, a_3 of the hexagons are in similar relation to the three main phases of the "major" system and may be directly supplied from the same, as may also the corners b_1, b_2, b_3 be similarly supplied.

It will be understood that, just as in the case of Fig. 7, power is transmitted both by the two six-phase systems and by the single-phase (or equivalent) system, and reconverted at the receiving end in the form of a joint three-phase supply on to the low-tension busbars, so in the case of Figs. 9 and 11 the three six-phase systems each transmit power in conjunction with the "major star" system, the latter working at from 100 000 to 150 000 volts, according to whether it is decided to risk a maximum potential gradient of 60 000 V/cm (as is, the author understands, at present under contemplation with three-phase cables) or of only 40 000 V/cm.

With regard to the actual capacitances of the various cores of the cable shown in Fig. 6, the author has worked out the various individual capacities between core and core.

The actual capacity currents required for each 15-mile section of the line are shown diagrammatically in Fig. 14. The calculations by which these figures are arrived at are shown in Appendix D.

The author has developed a simple arrangement which he thinks would be very valuable on long lines in the direction of reducing the drop due to this capacity current, and this will now be described.

THE TRANSMISSION OF CHARGING CURRENT THROUGH THE CENTRAL CORE.

Referring to Fig. 12, in the top part of the diagram is shown the way in which the aggregation of all the capacity current components of the lines involves a very heavy capacity current being sent along the outer cores from the generating station. This has rather deleterious effects on the voltage regulation of the sections of the step-up transformers and of the line.

In the lower part of Fig. 12 is shown how, by the establishment of one or two substations of comparatively small capacity along a long line (from which power would be supplied for commercial purposes for traction or lighting), it is quite practicable to "feed in" at the substations the capacity currents for the different insulation "rings" of the cable, and to transmit this current at the full 100 000 volts, re-transforming it to the local voltages required. The small hexagons shown are of course in connection with only one phase of the principal three-phase transmission (see also Fig. 11 where A, B, C represent the principal transmission).

It is arranged that at, for instance, substation No. 1 the 100 000-volt three-phase supply from the innermost cores of the six three-phase cables is taken through the three-phase primary shown, and on each phase there is generated in the secondary winding a 30 000-volt current which is fed directly, as shown, on to the correct chord of the hexagon of voltages. A feature of the author's arrangement is the following:—

A rather greater amount of reactance than the normal

is introduced in each primary or secondary winding, with the result that the transformer tends to over-regulate to capacity currents and to under-regulate to load or lagging currents, again with the result that the transformer does not tend to pick up any of the load current, but does attempt to pick up a certain amount of the capacity current. This causes it to feed capacity current into the intermediate and outer cores of the cables in each direction from the substation, at the expense of an additional current in the central core. As, however, the central core is working at 100 000 volts, it is obvious that the capacity current—being only a quadrature current with reference to the load current—can be easily allowed for by a comparatively small amount of copper in the core.

By the arrangement proposed, therefore, we have system would operate at 60 000 volts. Later, when the load developed, the second or lower six-phase system shown in Fig. 7 could be added, in such a sense that its instantaneous diametral E.M.F. would run upwards (on the diagram) at the same time as that of the upper hexagon. Its highest point, however, as well as that of the lowest point of the upper hexagon, being at earth potential, it would now be practicable to add the single-phase transformer, the secondary of which is shown by the thick, black vertical line in Fig. 8, and by this means to transmit over the same lines a single-phase superposed current at 123 000 volts, which could be similarly transformed at the distant end and would considerably increase the carrying capacity of the two six-phase systems. Lastly, when the load of the system warranted it the

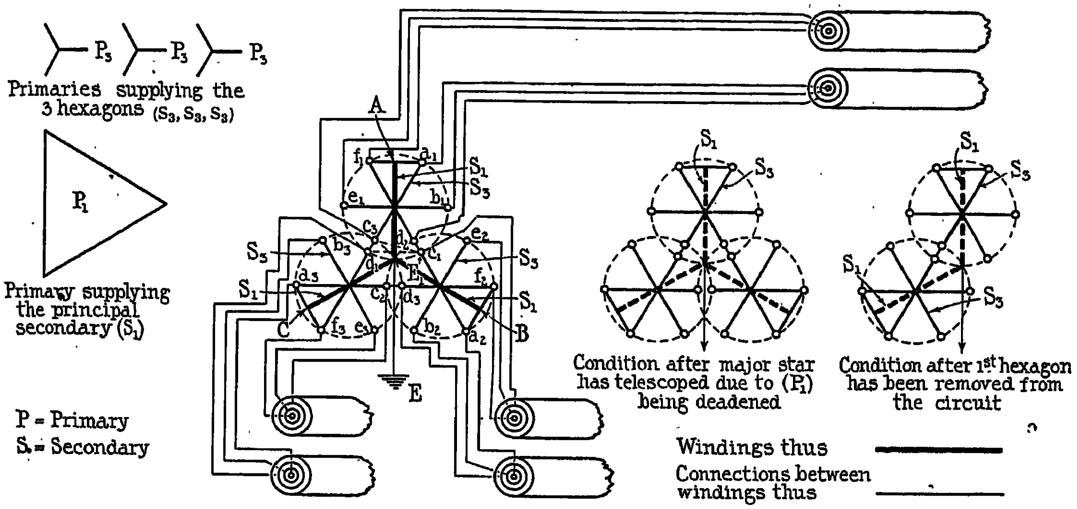

FIG. 11.—Connections at the step-up end.

SEQUENCE OF OPERATIONS ON REDUCED LOAD.

(1) Oil switch of transformer P_1 is tripped (and, if faulty, the hexagon of the faulty circuit is disconnected).
(2) Earth switch is kept from neutral point Q of hexagons to earth.
(3) Hexagon No. 1 is removed.
(4) Hexagon No. 2 is removed.
(5) Hexagon No. 3 is left in.

greatly reduced the amount of capacity current to be passed out from the central station through the intermediate and external cores, because we can feed into the line at as many points as may be found desirable (the maximum length to be fed varies inversely as the number of feed points), and therefore the central station has now to supply only the capacity current for the said cores for the first quarter-section of line (if there is a mid-way substation).

ADAPTING INITIAL EXPENDITURE TO INITIAL CAPACITY.

Reference may here be made to another feature of the author's system. Considering Fig. 7, it will be understood that the transmission system represented by the upper six-phase hexagon could be started, in the first instance, by itself, its bottom point being directly earthed, and thus the initial capital expenditure would be reduced. Under these circumstances the balance of the three-phase network, shown in Figs. 9 (I), 10 and 11 could be added and the vector relations of the E.M.F.'s could easily be altered so as to conform with Fig. 10, the 123 000-volt single-phase supply being now replaced by a 100 000-volt three-phase supply.

V. CERTAIN FEATURES OF THE AUTHOR'S SYSTEM.

In Section (3) the advantages of a six-phase system were pointed out from the point of view of the distribution of the potentials between the various cores of the triple-concentric cables, but another point of view that must not be lost sight of is as follows:—

The employment of a six-phase system, carried from each limb of the principal three-phase transformer system, fulfils another function of great value in that it not only provides a system of subdivided cores in which all the cores must be heavy (and hence incapable of fusing under heavy capacity currents), but, in addition, it utilizes all those cores equally for the

passage of heavy load currents without seriously diminished voltage on each circuit; whereas, if the same result had been attempted by the mere tapping of a single-phase transformer, as in Fig. 5, the operating voltage on one of the circuits would have been seriously lowered, and that on the other reduced to such a degree as to be virtually altogether ineffective for power transmission. This provides a sufficient excuse for returning to the employment of "intersheaths."

Greatly increased reliability in operation, whereby a duplicate cable line—such as is proposed in Appendix B, in connection with the scheme embodying plain single-core cables—is rendered unnecessary, is provided by the arrangements about to be described in the present section.

Fig. 11 gives an analysis of the arrangements, showing more particularly the way in which the line is sectionalized, whether on account of a breakdown or with the object of preserving "regulation" and reducing the (total) charging current when the load is reduced.

An advantage of the proposed scheme is that if, for example, the two cables attached to phase A (see Fig. 11) were both to fail, when, in the ordinary way of operating three-phase systems, no three-phase power could any longer be transmitted, the two remaining six-phase systems may, in the author's system, be arranged to continue to work as though nothing had happened. If, moreover, only one cable had failed, and not two, then three-phase power could still have been transmitted over the "major star" system ABC (using the remaining sound cable for the third leg) in addition to six-phase power over two out of the three six-phase systems. (It will be shown later in the paper that the chance of even one cable completely breaking down sufficiently to be incapacitated is very much more remote than with an ordinary single-core cable.)

Thus—and this would be still more feasible under the conditions shown in Fig. 9 (IV)—with a little overloading of the transformers the whole power supply could be maintained; particularly if the central core of each cable were made of double section, which would not appreciably raise the cost of the whole cable at the voltage considered. In connection with the reliability in working thus offered, Mr. Philip Torchio of New York has stated that "the assuring of reliable operation is vastly more important than getting the maximum rating out of a certain mass of metals."

The sectionalizing of the system incidentally provides also a means: (1) of insuring regulation without the use of rotary condensers, and (2) of greatly reducing the charging current of the line at light loads. For example, if, on a reducing load, the various sections of transformers be de-electrified in the order indicated in Fig. 11, then each section of the line and transformers remaining in service is kept fully loaded, and thus capacity current-rises are avoided.

The total line-charging current (a very important matter) and also the total hysteresis loss are similarly reduced, by the fact that progressively less and less cable is left in circuit.

The design of the cable itself is particularly suited to avoid breakdown (due to outside influences), as will be appreciated from Fig. 6, which shows a cross-section of the cable.

The function of the internal lead sheath will be understood from the following considerations:—

Cables, as laid nowadays, are fairly immune from

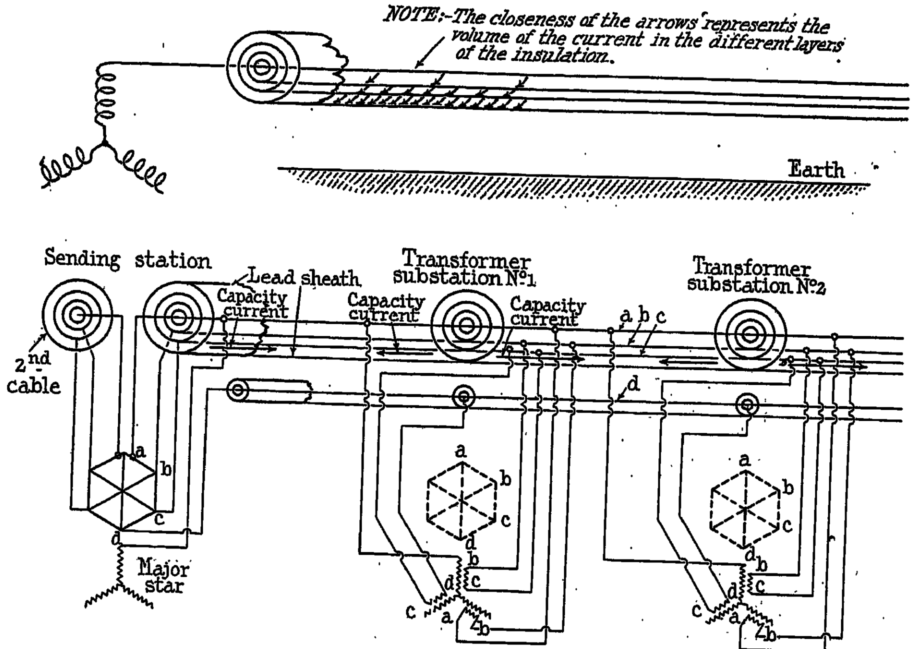

FIG. 12.—Arrangement for relieving the cores of capacity current in the case of a very long line. (*Note.*—Currents in "b" are, for clearness, omitted.)

the blow of a pick; but the lead sheath may crack, or crystallize, or possibly be attacked by acids or by electrolysis.

The first intimation of a fault is given by the failure of the outermost insulation. If this is made to trip immediately, in the first place, the oil switch governing whichever of the transformers P_3 (see Fig. 11) feeds the faulty six-phase circuit, and simultaneously the "major" transformer P_1 feeding that section (and assuming that the action has been sufficiently rapid to prevent the copper of the outer conductor being burnt through), we have the penultimate lead sheath still unpierced and the cable still capable of working —under slightly increased stress—for days if necessary, until a spare piece of cable can be connected in the secondary side of the step-up transformer at a time of light load. If there were no inner lead sheath below the core, moisture would reach the insulation, and it might only be a question of hours before it again broke down. The three independent six-phase systems permit of repair work being done without any material interruption to the supply, at times of light loads.

The cable shown in Fig. 6 has been designed to work at about 30 000 volts between the innermost conductor and the intermediate conductor, at an equal pressure between the intermediate conductor and the outermost conductor, and with about 17 800 volts between the outermost conductor and the lead sheath. Under these conditions the maximum potential gradient on the innermost and intermediate conductors will be approximately 39 000 and 29 000 V/cm respectively, while that on the outermost conductor will be about 20 000 V/cm.

At the joints the potential gradient could be kept down by swelling the conductors gradually, in the manner indicated in Fig. 13. Those parts where the potential gradient was highest would be entirely insulated at the makers' works as shown, leaving a reduced stress to be borne by those parts insulated on site.

Hysteresis Loss.

The loss due to hysteresis on the 100 000-volt three-phase/six-phase system is only about 1·9 per cent on a 30-mile line, or about 0·9 per cent more than with a 30 000-volt transmission of equal power (50 000 kW), but on a 40 per cent load factor this would be halved on the former system.

Regulation.

The regulation voltage-drop in the 30 000-volt line discussed in Appendix A for a 30-mile line is 5·9 per cent; while the total amount of copper is 2 040 tons, representing an outlay of, say, £180 000. The regulation "drop" in the 100 000-volt 30-mile line discussed in Appendix B (plain single-core cables) is 4·5 per cent, while the total amount of copper is 460 tons, representing an outlay of, say, £41 400.

On the six-phase/three-phase system the regulation "drop" is roughly 5 per cent, and the amount of copper about 700 tons, representing an outlay of, say, £63 000. These quantities would be divided by three for a 10-mile line.

The author thinks it will be conceded that where a trunk line interlinking two cities is run along the lines of railway joining these two cities, and where there is any possibility of supplying current from such a trunk line for the working of the railway system, it is highly desirable that the regulation of the line should be so good that the throwing on and off of the railway loads will not seriously affect the regulation at the substation end; also that, allowing for the additional loss in regulation after the public supply of current leaves the substation, in distribution, it is inadvisable that the regulation of the trunk line, including its step-up and step-down transformers, should be more than $12\frac{1}{2}$ per cent. By fixing the declared voltage at that obtained on half load the variation of voltage is of course reduced from $12\frac{1}{2}$ per cent to $6\frac{1}{4}$ per cent.

The author thinks it will also be conceded that induction regulators, to cover a large range in the voltage and operate automatically, are very costly and undesirable, particularly if they can be dispensed with.

It will be noted from Appendix A that, in the case of the 30 000-volt line considered, the resistance-drop is of the order of 3·3 per cent, the reactance-drop of the order of 1·6 per cent, and the capacity-rise of the

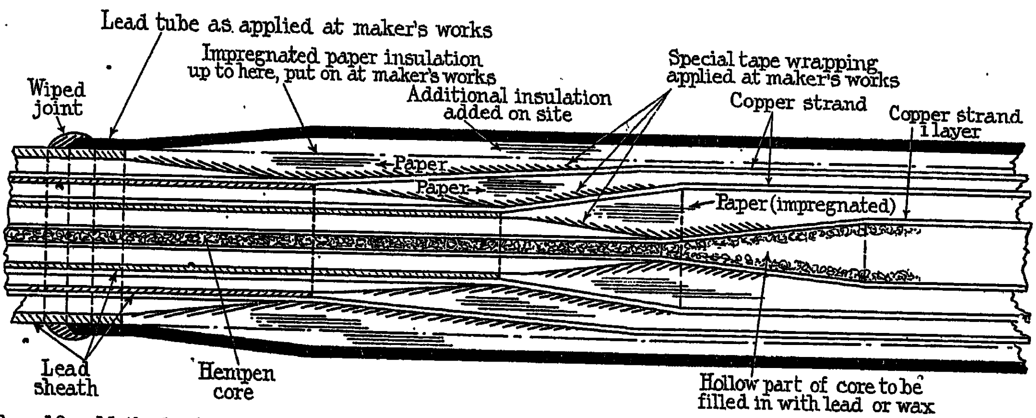

FIG. 13.—Method of finishing-off the end of the cable so as to reduce the potential gradients at the approach to a joint; performed at makers' works.

order of 1 per cent; i.e. a total "regulation" of 5·9 per cent on the line alone. If to this we add, say, $4\frac{1}{2}$ per cent on the step-up transformers (due largely to capacity current), and $3\frac{1}{2}$ per cent on the step-down transformers, we have a total of 13·9 per cent, or, say, 14 per cent, which is rather high for satisfactory regulation in view of what has been stated above.

It will possibly be objected that the author has done an injustice to the 30 000-volt scheme in adopting for this a current density of only 500 amperes per square inch, and that half the number of cables could be employed, working at a current density of 1 000 amperes per square inch. If, however, this were done, and regardless of the extra energy loss in the cables (which will be dealt with elsewhere), the "regulation" of the cables and transformers would be increased from 13·9 per cent to 19·8 per cent, and the author submits that the latter regulation is entirely impracticable without a very great outlay in induction regulators and considerable expense in the maintenance of the same.

On the other hand, by adopting a pressure of 100 000

Charging Current.

The charging current for 30 miles on the author's system represents 61 200 kVA leading wattless current, but at light loads this would be reduced to roughly 20 000 kVA, which is less than would obtain with a 30 000-volt system transmitting equal power (the figure for which is approximately 33 500 kVA), and entirely neglects the possible savings due to the better distribution of heat, and consequently greatly lowered power factor, which was discussed earlier in the paper.

The calculations by which the figure of 61 200 kVA is arrived at will be found in Appendix D, in connection with the capacities on the author's system, and the results there obtained are represented diagrammatically in Fig. 14.

Charging Current fed from Reactance of Motor Load.

With suitable precautions to avoid "current resonance," the author believes that the necessary charging

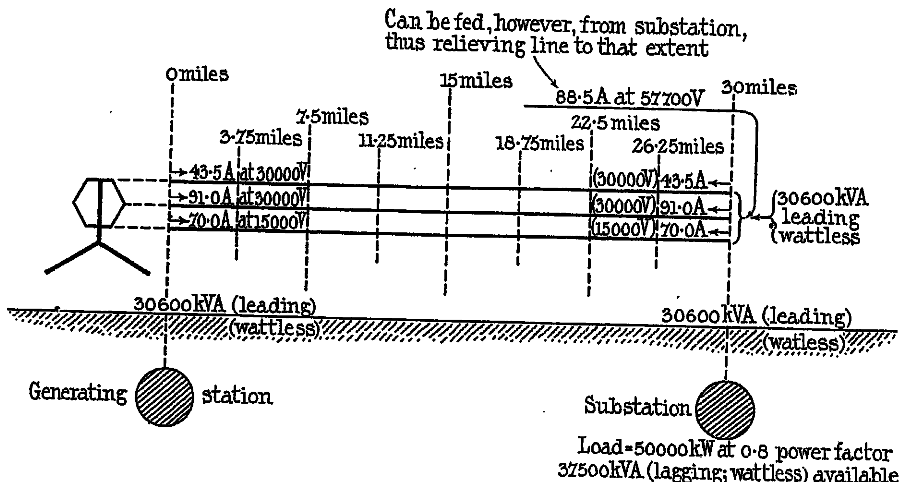

Fig. 14.—Distribution of capacity currents on 100 000-volt transmission. No demand on substation for lagging wattless current.

volts and using single-core cables, the line drop (exclusive of transformers) is reduced to $4\frac{1}{2}$ per cent, as given in Appendix B, and thus the total regulation becomes only $12\frac{1}{2}$ per cent, as against 19·8 per cent on the 30 000-volt scheme with 5 cables in parallel.

As already explained, by suitably fixing the declared voltage this variation may be halved, but even $6\frac{1}{4}$ per cent is distinctly high, and it may be necessary to eliminate the regulation of the step-up transformers by operating at the generating station with a constant voltage on the high-tension secondaries, instead of attempting to keep the low-tension busbars at a constant pressure. If there are any large loads in the vicinity of the station which are supplied from the low-tension busbars, the regulation of this section of the system will of course be impaired, and the employment of regulators on the primary or secondary sides of the transformers may be necessary, or, alternatively, a step-down transformer may be used for the local load.

currents may be fed into the line at convenient points in such a way as to avoid passing any charging current along the central cores, thus opening up the possibility of removing the disability under which a.c. transmission now labours as compared with d.c. transmission. This method has not, however, been considered in the calculations given in Appendix D.

Fig. 15 illustrates the resultant distribution of capacity currents under these conditions.

On such a line, loads having a power factor of only 0·7 would be invited, and a.c. railway electrification with single-phase motors at 25 periods might, in some cases, be employed if otherwise found desirable.

VI. Reasons for the Selection of 10 Cables on a 30 000-volt Scheme.

It will be well here to state the reasons which determined the author in selecting what is apparently

a very large number of cables in parallel to deal with the load under consideration.

It has already been explained that, on questions of regulation alone, it appeared to be a necessity that 10 cables should be employed, on the assumption that it was undesirable to make the cables of greater sectional area than 0·25 square inch per core.

There is, however, the alternative point of view to be considered, viz. as to whether the additional waste of energy involved by using only 5 cables would not cost more, when capitalized, than the difference in price between 5 cables and 10 cables. This point the author has investigated carefully, with the following results: On an output of 7 500 kW (the figure taken by Mr. W. M. Selvey*), with 8 000 hours per annum (91·5 per cent load factor), and with coal at 0·15d. per unit generated, the annual value of 600 000 units wasted (corresponding to 1 per cent of the total number of units generated) would represent £375.

Converting the above figures to our present case, we have:—

$$£6\,000 \times \frac{0\cdot 5\text{d.}}{0\cdot 15\text{d.}} \times \frac{50\,000 \text{ kW}}{7\,000 \text{ kW}} \times \frac{40\ \%\text{ load factor}}{91\cdot 5\ \%\text{ load factor}} = £58\,300$$

In other words, it will pay to invest £58 300 in extra copper in the transmission line in order to save 1 per cent of the total power generated.

The 0·5d. per unit is for the supply to the substation; but as the line loss is a peak load loss, and varies with the square of the load, and has in consequence a poorer load factor than the load itself, these waste units will certainly be more expensive than units sold to the substation for power, and they should therefore be charged at a higher rate.

The following is another way of regarding the matter: An extra 1 000 kW demanded at the generating station means the loss of the sale of that power (less losses) to a

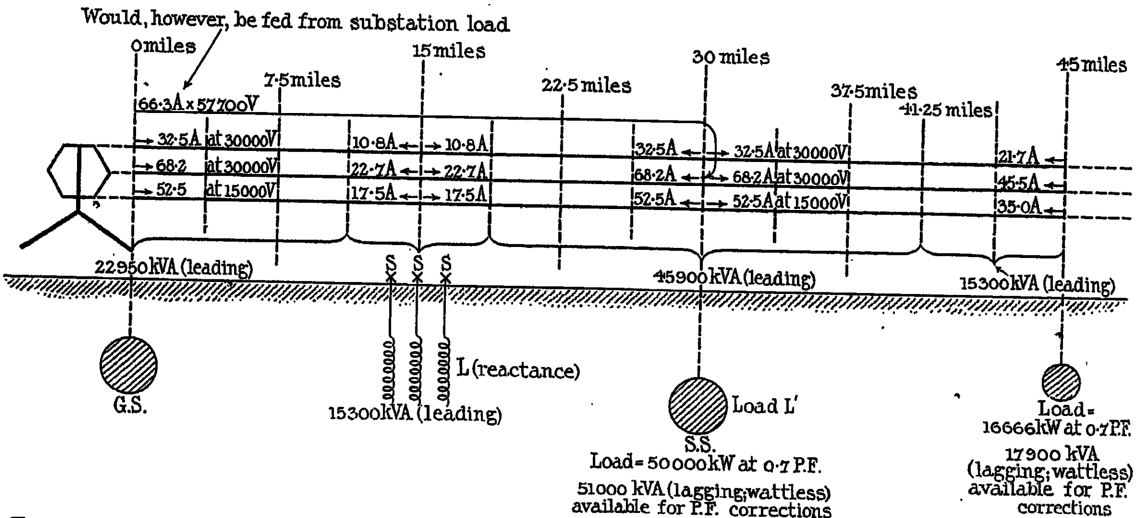

FIG. 15.—Distribution of capacity currents on 100 000-volt transmission. Lagging wattless current supplied from substation load.

For the purpose of showing the value of each additional 1 per cent of efficiency gained in the generating plant, Mr. Selvey took an 8-years' basis and capitalized the above £375 per annum at £3 000. From this he deduced that it would pay, on a plant of the above magnitude, to spend an extra £3 000 on generating plant (which had a life of only 8 years) in order to gain 1 per cent in efficiency, i.e. in order to save 1 per cent of the power. In other words, the sum of £375 saved every year would enable one to continue to spend an additional £3 000 once very 8th year on a more efficient generating plant, when one renewed the latter.

If, however, we are dealing with a transmission cable which has a life of, at the very least, 16 years, it will obviously pay to invest an additional £6 000 (i.e. double) for an equal 1 per cent saving in the I^2R losses in the line.

consumer, and the loss of the revenue that would thereby accrue, and therefore covers all charges up to the consumer's premises; and if in addition to this we make an allowance for the poor load factor of the I^2R losses in the transmission line, this proportionately further aggravates the charge.*

It seems advisable, in view of the above, to correct the charge per unit for a "loss" load factor of, say, 30 per cent (I^2R losses), and hence to multiply the above figure of £58 300 by 40/30, which gives £77 800 as the capitalized value of a 1 per cent loss in the line.

Referring now to Appendix A, we see that the losses consist of

3·3 per cent plus 1·58 per cent plus 3·55 per cent (wattless current × resistance)
= 8·4 per cent total as a sufficiently near approximation.

* W. M. SELVEY: "Power Plant Testing," *Journal I.E.E.*, 1915, vol. 53, p. 109.

* In this connection, see the remarks by Messrs. J. R. Beard, J. A. Morton, and H. M. Sayers in the discussion on Mr. W. B. Woodhouse's paper (*Journal I.E.E.*, 1921, vol. 59, p. 85).

Hence, 8·4 times £77 800 = £653 000; and therefore, in order to make it pay to put 5 cables in parallel instead of 10, the difference in capital cost should be of the order of £653 000, to which would have to be added, say, £50 000 (to £100 000) on account of induction regulators, making a total of, say, £703 000.

The author has therefore assumed that it will be agreed that, quite apart from the question of regulation, it is the best policy to put down the double section of copper, even though this entails working at a comparatively low current density.

VII. Conclusions.

It is hoped that the following points have either been established or will be clear from the matter given in the paper :—

(1) By the introduction of intersheaths between which a *constant* difference of potential is maintained (see Table 2, page 234) a gain of 47 per cent is effected in the voltage absorbed, for a given thickness of insulation.

(2) By the introduction of intersheaths having a steadily *increasing* difference of potential between them, working from the central core outwards (see Table 3, page 234) a further gain of 50 per cent—i.e. a total gain of 120 per cent—is effected in the voltage absorbed, without appreciably more energy loss in the dielectric than in the case of Table 2.

(3) The enormous effect of temperature upon the resistivity of the dielectric warrants the employment of any conceivable methods—such as those indicated in the paper—which will relieve the temperature on the innermost layers of the dielectric.

(4) The separation of the principal phases in the system proposed, or in any single-core system, carries with it a much greater freedom from complete short-circuits.

(5) Double reliability is offered by having two cables per (principal) phase, this being approximately equivalent to a spare cable and, in the case of a single-core 100 000-volt system, to two spare cables.

(6) The virtual elimination of all faults, except those to earth, is effected, and interruptions caused by such faults are reduced to such a degree that the working of the system is not seriously affected.

(7) Considerable improvement in step-up and step-down transformer regulation is provided, as compared with that in three-core cable systems operating at 30 000 volts, or single-core systems operating at 100 000 volts.

(8) The initial capital outlay is limited to the natural growth of the load.

(9) As compared with a 30 000-volt three-core cable, there is no waste space in the centre of the cable.

(10) Assuming that the line can be made self-exciting, the difficulty in connection with feeding the capacity currents to the line disappears, and very much longer transmissions can be attempted than would otherwise be practicable, or are considered in the paper.

The author wishes to acknowledge, with many thanks, the assistance which he has received in compiling the paper and the following Appendixes, from the following firms :—Messrs. Callender's Cable and Construction Co., Ltd., Messrs. Henley's Telegraph Works Co., Ltd., Messrs. British Insulated and Helsby Cables, Ltd., Messrs. W. T. Glover and Co., Ltd., and Messrs. Pirelli General Cable Works, Ltd. (cable companies); Messrs. Reyrolle and Co., Ltd., Messrs. British Thomson-Houston Co., Ltd., Messrs. Metropolitan-Vickers Electrical Co., Ltd., and Messrs. General Electric Co., Ltd. (switchgear companies); and Messrs. Metropolitan-Vickers Electrical Co., Ltd., Messrs. Brush Electrical Engineering Co., and Messrs. Johnson and Phillips, Ltd. (transformer companies).

APPENDIX A.

Ordinary Three-phase Working.

Power to be delivered = 50 000 kW at 0·8 power factor.

Voltage at receiving end = 30 000 V.

Length of line = 30 miles.

Cable used: ordinary three-core cable (as in Fig. 16).

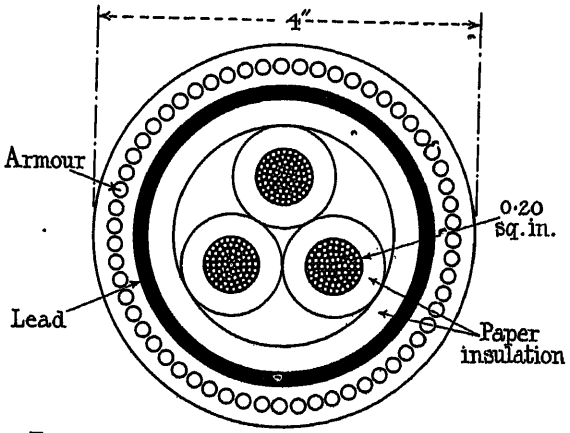

Fig. 16.—Cable for 30 000-volt transmission.

Resultant current per phase = 1 200 amperes. (This current will be passed through ten 0·25 square inch cables in parallel, excluding spares.)

"Work" component of the above current = 960 amperes (I_L).

Lagging component = 728 amperes (I_W).

Current density = 120/0·25 = 500 amperes per square inch (neglecting capacity current).

Capacity current = $b \times E$ = 0·00372 × 17 320 = 64·5 amperes per cable.

Total capacity current (10 cables) = 645 amperes.

The figure 0·25 sq. in. for the cross-section is some-

what unduly liberal, but is retained in order to keep the copper voltage-drop within reasonable limits.

Take, therefore, in comparing copper weights, the following :—

Total cross-section of copper = 0·25 sq. in. × 3 cores (per cable) × 10 cables = 7·5 sq. in.

The amount of copper involved = 2 040 tons per 30 miles.

Below are the calculations giving the various components of the E.M.F. with their phase relations :—

$I = 960\text{A} - j728\text{A}$ (0·8 power factor).

$r = 0{\cdot}2$ ohm × 30 miles = 6·0 ohms (hot).

$x = (0{\cdot}4 \times 10^{-3}) \times 2\pi f \times 30 = 3{\cdot}76$ ohms.

$b = 2\pi f C = 6{\cdot}28 \times 50 \times (0{\cdot}4 \times 10^{-6}) \times 30$ miles.

$= 0{\cdot}00372$ mho.

$$\left.\begin{array}{l} Z = r + jx = 6{\cdot}0 + j3{\cdot}76 \\ Y = g + jb = 0 + j0{\cdot}00372 \end{array}\right\} \begin{array}{l} \therefore ZY = j0{\cdot}0223 - 0{\cdot}014. \\ \therefore \tfrac{1}{2}ZY = -0{\cdot}007 + j0{\cdot}0111. \end{array}$$

$1 + \frac{1}{2}ZY = +\,0{\cdot}993 + j0{\cdot}0111.$

$$E_G = E_R(1 + \tfrac{1}{2}ZY) + (r + jx)(I_L/10 + jI_W/10)$$

$$= \underset{(1-\frac{1}{2}bx)\quad (j.\frac{1}{2}br)}{17\,320\,(0{\cdot}993 + j0{\cdot}0111)}$$

$$+ \underset{(r)\qquad (jx)}{(6{\cdot}0 + j3{\cdot}76)}\,(\overset{I_L}{960\text{A}/10} - \overset{jI_W}{j728\text{A}/10})$$

$$= \underset{\substack{E_R - E.\frac{1}{2}bx \\ (17\,320-170)}}{17\,150} + \overset{jE.\frac{1}{2}br}{j193} + \overset{rI_L}{576} - \overset{jrI_W}{j425} + \overset{jxI_L}{j360} + \overset{xI_W}{274}$$

$$= 1\% \quad 1{\cdot}1\% \quad 3{\cdot}3\% \quad 2{\cdot}45\% \quad 2{\cdot}1\% \quad 1{\cdot}58\%$$

Total regulation "drop" $= rI_L + xI_W + \frac{1}{2}bEx.$

$= 3{\cdot}3\,\% + 1{\cdot}58\,\%$

$+ 1{\cdot}0\,\% =$ (say) $5{\cdot}9\,\%$.

APPENDIX B.

Plain Single-core Scheme (see Fig. 1) with 100 000 Volts between Phases.

Power to be delivered = 50 000 kW at 0·8 power factor.

Length of line = 30 miles.

Cable employed: as shown in Fig. 1, 6 single-core 0·185 sq. in. cables (100 per cent spares included).

Voltage at receiving end = 57 700 volts (to neutral).

Resultant receiver current, neglecting capacity current = 360 amperes per phase.

"Work" component of the above current = 288 amperes (I_L).

"Lagging" component = 216 amperes (I_W).

Current density = 1 000 amperes per square inch (excluding capacity current), = 1 400 amperes per square inch (including capacity current).

Capacity current $= b \times E = 0{\cdot}0033 \times 57\,700$, 190 amperes per cable.

Total capacity current (2 cables) = 380 amperes.

Below are given the components of the voltage lost in the line, and their phase values.

The preliminary calculations for the various "constants" of the line are as follows :—

$I = I_L - jI_W.$

$= 288\text{A} - j216\text{A}$ (0·8 power factor).

$r = 0{\cdot}27$ ohm × 30 miles = 8·1 ohms (hot).

$L = 0{\cdot}4605 \log_{10} b/a + 0{\cdot}05 + L'$ (negligible).

$= 0{\cdot}70 \times 10^{-3}$ henry.

$x = (0{\cdot}70 \times 10^{-3}) \times 2\pi f \times 30 = 6{\cdot}6$ ohms.

$$C = \frac{0{\cdot}0388 \times 3{\cdot}2}{\log_e b/a} = 0{\cdot}35\ \mu\text{F per mile.}$$

$b = 2\pi f C = 6{\cdot}28 \times 50 \times (0{\cdot}35 \times 10^{-6}) \times 30$ miles

$= 0{\cdot}00330$ mho.

$$\left.\begin{array}{l} Z = r + jx = 8{\cdot}1 + j6{\cdot}6 \\ Y = g + jb = 0 + j0{\cdot}0033 \end{array}\right\} \begin{array}{l} \therefore \tfrac{1}{2}ZY = -0{\cdot}0109 + j0{\cdot}0133 \\ = j0{\cdot}0267 - 0{\cdot}0218. \end{array}$$

$1 + \frac{1}{2}ZY = 0{\cdot}9891 + j0{\cdot}0133.$

$$E_G = E_R(1 + \tfrac{1}{2}ZY) + (r + jx)\,(\tfrac{1}{2}I_L + jI_W).$$

$$= 50\,770\ (0{\cdot}9891 + j0{\cdot}0133)$$

$$+ (8{\cdot}1 + j6{\cdot}6)\,(\overset{I_L}{288\text{A}/2} - \overset{jI_W}{j216\text{A}/2}).$$

$$= 57\,700 - \overset{(\frac{1}{2}bEx)}{\underset{1{\cdot}25\%}{700}} + \overset{j(\frac{1}{2}bEr)}{\underset{1{\cdot}33\%}{j768}} + \overset{rI_L}{\underset{2{\cdot}0\%}{1\,165}} - \overset{jrI_W}{\underset{1{\cdot}5\%}{j882}}$$

$$+ \overset{jxI_L}{\underset{1{\cdot}65\%}{j950}} + \overset{xI_W}{\underset{1{\cdot}25\%}{710}}$$

Total regulation "drop" $= rI_L + xI_W + \frac{1}{2}bEx.$

$= 2{\cdot}0\,\% + 1{\cdot}25\,\%$

$+ 1{\cdot}25\,\% = 4{\cdot}5\,\%.$

The amount of copper involved, allowing for 3 sets of cables = 460 tons per 30 miles.

Note.—The leakage conductance (g) of the dielectric has been neglected in the above calculations. In a more rigorous calculation account would have to be taken of it (see additional Note in Appendix D on this subject).

APPENDIX C.

Further Remarks on the Question of Potential Gradients.

The following notes give the result of a continued investigation on the lines indicated in Section III of the paper.

In Table 1 are given in tabulated form the values of

(1) The capacity of the 1st, 2nd, 3rd, 4th, . . . 10th, etc., layers of insulation, working outwards.
(2) The corresponding capacity current passing radially through these layers.
(3) The watts lost in each layer.
(4) The voltage differences across each layer.
(5) The volume of each layer, in cubic centimetres.
(6) The watts per cubic centimetre.
(7) The maximum potential gradient on each successive section.

It will be observed that the total voltage absorbed down to the end of the tenth layer is 41 250 volts. The above figures merely correspond to development

In Table 2 corresponding figures are given, but this time on the assumption that the voltages between successive equipotential surfaces are constant at 8 750

TABLE 1.

Decreasing Voltage Differences between Successive Layers.

$C \times 10^{-6}$ per foot	Capacity current ($= i_d \times 10^{-3} = 2\pi fCE$)	Watts lost ($= W_d$) per foot	Voltage absorbed, E	Value of $\log_e \frac{b}{a}$	Relative contents of each layer	Watts per cm³	Max. potential gradient, G
					cm³		
0·000124	0·341	0·0450	8 750	0·432	54	0·000834*	30 000
0·000131	0·320	0·0370	7 720	0·405	117	0·000316	19 050
0·000185	0·321	0·0270	5 700	0·288	165	0·000163	13 000
0·000238	0·322	0·0200	4 030	0·223	213	0·000094	9 510
0·000302		0·0170	3 550	0·184	261	0·000065	7 800
			29 750				
0·000351		0·0140	2 890	0·152	306	0·000046	6 350
0·000399	$0·32 \times 10^{-3}$ (constant)	0·0120	2 500	0·131	354	0·000034	—
0·000461		0·0110	2 230	0·117	402	0·000027	—
0·000511		0·0097	2 020	0·106	450	0·000021	—
0·000560		0·0085	1 840	0·097	489	0·000017	—
		0·2012	41 250		2 820		

TABLE 2.

Constant Voltage Differences between Successive Layers.

0·000124	$0·341 \times 10^{-3}$	0·0450	8 750	0·432	54	0·000834*	30 000
0·000131	0·362	0·0472	8 750	0·405	117	0·00040	21 600
0·000185	0·491	0·0635	8 750	0·288	165	0·00038	20 000
0·000238	0·694	0·0940	8 750	0·223	213	0·00044	20 500
0·000302	0·790	0·1030	8 750	0·184	261	0·000396	19 250
0·000351		0·3527	43 750		810		
0·000399							
0·000461							
0·000511							
0·000560		75 per cent more (total) loss than with "tapering" E.M.F.					

TABLE 3.

Increasing Voltage Differences between Successive Layers.

				$1/(\log_e b/a)$			
0·000124	0·227	0·020	5 820	2·31	54	0·000370*	20 000
0·000131	0·340	0·045	8 920	2·47	117	0·000385	22 000
0·000185	0·615	0·098	10 600	3·47	165	0·000594	24 200
0·000238	0·843	0·142	11 300	4·48	213	0·000668	26 600
0·000302	1·270 (0·635)	0·259 (0·0635)	13 320 (6 660)	5·44	261	0·000486	29 300
0·000351		0·559 (0·368)	49 960 (43 300)	6·58	810		
0·000399							
0·000461							
0·000511							
0·000560		4 per cent more (total) loss than with constant voltage per section.					

* The first layer, not being a full half centimetre thick, is not properly representative of the others.

further outwards on the cable of the figures given in 3, and assume the curve of potential gradient to that given in Fig. 3.

volts, instead of diminishing according to the figures given, as in Table 1. In this case it will be observed that after reaching the fifth ring of insulation, cor-

responding to a radius of 3 cm, 43 750 volts has been absorbed in the insulation. It will also be noticed that the watts lost in the insulation up to this point due to the condenser current alone are now 0·3527 as against 0·2102 in Table 1, i.e. an increase of 75 per cent. The watts lost per cubic centimetre on the innermost layer are, however, identical with those in Table 1 and this is the criterion by which we have to abide (from the point of view of heating).

Therefore, in putting relatively more stress upon the succeeding layers as we work outwards, as compared with those in Table 1, we have reduced the effective radius of the insulation from 5 cm to 3 cm, i.e. the size of the cable necessary to absorb 43 750 volts would be reduced in that proportion. The comparison would be much more marked if we had carried the readings in Table 1 further, as will be evident from a consideration of these readings.

In Table 3 particulars similar to those given in Tables 1 and 2 are worked out, but this time on the basis of actually increasing the voltage differences between the successive layers, instead of keeping them constant as in Table 2 or reducing them as in Table 1. It will be seen that the potential gradient in the ring of insulation next to the core is now reduced to as low as 20 000 V/cm as compared with 30 000 V/cm in Tables 1 and 2. By adding up the voltages absorbed it will be seen from Table 3 that 49 960 volts have been absorbed by the time the 3 cm radius has been reached. This is more than is required and therefore the pressure upon the outermost slice of insulation might be considerably reduced, as shown, for instance, by the figures given in brackets. It will be noted that if we had not reduced the potential gradient of this outermost slice the total watts lost due to hysteresis would be rather more, namely 0·559, but that if the pressure is reduced to 6 660 volts the total watts lost will only be 0·368, a result virtually identical with that obtained in Table 2, but with the great advantage of reducing by over 50 per cent the watts per cm^3 next to the core.

Bearing in mind what was previously put forward, viz. that, in the ordinary working of the cable, the heat generated in the copper core due to the load current causes the slices of insulation to be progressively hotter towards the centre of the cable, it will be seen that a great advantage would be obtained by generating the greater proportion of the heat due to dielectric hysteresis in the slices of insulation that are naturally at a much lower temperature, and in which, instead of the dielectric power factor remaining constant from the central core outwards, as is assumed in Tables 1, 2 and 3, it would consequently be diminishing, with still better results than those shown in the tables.

In addition to the above it must be remembered that not only does the heat due to the loss in the copper produce temperatures in the innermost layers of insulation greatly above those in the exterior layers, but that the conductance losses due to pure leakage of current (which are not taken account of in Tables 1, 2 and 3), also produce heating under conditions precisely similar to those of dielectric hysteresis. The advantage gained in the dielectric hysteresis loss is practically doubled (and may be quadrupled) by that gained in the pure conductance loss through the dielectric.

APPENDIX D

Calculations of Capacities of Triple-concentric Cables.

Referring to Fig. 6, let the innermost, intermediate and outermost cores be designated a, b and c, respectively, and let the lead sheathing be designated d.

Let the dimensions be as follows :—

	cm
Radius of a	0·835
Radius to interior surface of core b	2·105
Radius to exterior surface of core b	2·300
Radius to interior surface of lead sheathing underneath core c	3·570
Radius to exterior surface of lead sheathing underneath core c	3·920
Radius to exterior surface of core c	4·120
Radius to interior surface of external lead sheathing	5·120
Radius to exterior surface of external lead sheathing	5·570

The capacities per mile of the three insulations are obtained as follows :—

$$C_{a/b} \doteq \frac{0 \cdot 0388 \times 3 \cdot 2}{\log_{10} (2 \cdot 10/0 \cdot 835)} = 0 \cdot 3095 \times 10^{-6} \text{ farad}$$

$$C_{b/c} = \frac{0 \cdot 0388 \times 3 \cdot 2}{\log_{10} (3 \cdot 57/2 \cdot 30)} = 0 \cdot 647 \times 10^{-6} \text{ farad}$$

$$C_{c/d} = \frac{0 \cdot 0388 \times 3 \cdot 2}{\log_{10} (5 \cdot 12/4 \cdot 12)} = 1 \cdot 00 \times 10^{-6} \text{ farad}$$

The total capacities for 30 miles are therefore :—

$$C_{a/b} = 0 \cdot 3095 \times 10^{-6} \times 30 = 9 \cdot 27 \times 10^{-6} \text{ farad}$$
$$C_{b/c} = 0 \cdot 647 \times 10^{-6} \times 30 = 19 \cdot 5 \times 10^{-6} \text{ farad}$$
$$C_{c/d} = 1 \cdot 00 \times 10^{-6} \times 30 = 30 \cdot 0 \times 10^{-6} \text{ farad}$$

The capacity currents through the three insulations are :—

$$I_{a/b} = b_{a/b} \times E = 2\pi \times 50 \sim \times (9 \cdot 27 \times 10^{-6}) \times 30\,000 \text{ V} = 87 \cdot 2 \text{ A}$$
$$I_{b/c} = b_{b/c} \times E = 2\pi \times 50 \sim \times (19 \cdot 5 \times 10^{-6}) \times 30\,000 \text{ V} = 183 \cdot 5 \text{ A}$$
$$I_{c/d} = b_{c/d} \times E = 2\pi \times 50 \sim \times (30 \times 10^{-6}) \times 15\,000 \text{ V} = 141 \cdot 5 \text{ A}$$

Now,

87·2 A × 30 000 V = 2 610 kVA; or 57 700 V × 45·2 A
183·5 A × 30 000 V = 5 500 kVA; or 57 700 V × 95·4 A
141·5 A × 15 000 V = 2 120 kVA; or 57 700 V × 36·8 A

kVA per cable = 10 230

Current per cable (central core) = 177·4 A

Taking the power factor at 1·5 per cent, the kilowatt loss due to dielectric hysteresis alone (i.e. neglecting leakage conductance loss) is :—

10 230 kVA × 0·015 × 6 (cables) = 918 kW

which is $918/50\,000 = 1\cdot84$ per cent of the power transmitted.

Total kVA capacity (wattless leading current) for a 30-mile section

$$= 10\,230 \text{ kVA per cable} \times 6 \text{ (cables)}$$
$$= 61\,200 \text{ kVA (approx.)}$$

Resistivity Loss in Dielectric.

The following first approximation to the resistivity loss (i.e. the "leakage conductance" loss) in connection with the author's system has been worked out, on the basis of the specific average effective resistivity per cubic centimetre being taken at 100×10^{10} ohms at 23° C. and at a potential gradient of 40 kV/cm; and the formula used is as follows:—

$$\text{Watts per cm length of cable} = \frac{E^2}{\frac{\rho_{(av.)}}{2\pi l}\int_a^b \frac{1}{r}dr}$$
$$= \frac{2\pi l \,.\, E^2}{\rho_{(av.)}\log_e(b/a)}$$

where $\rho_{(av.)}$ = average effective resistivity per cubic centimetre,
= (say) 100×10^{10} ohms per cubic centimetre; at 25° C. and at 40 kV/cm.

From the above formula we obtain:—

$$W_{a/b} \text{ (per mile)} = \frac{6\cdot28 \times (5\,280 \times 30\cdot5) \times 30\,000^2}{100 \times 10^{10} \times 2\cdot30 \times \log_{10}(2\cdot105/0\cdot835)}$$
$$= 985 \text{ watts (per cable)}$$

$$W_{b/c} \text{ (per mile)} = \frac{6\cdot28 \times (5\,280 \times 30\cdot5) \times 30\,000^2}{100 \times 10^{10} \times 2\cdot30 \times \log_{10}(3\cdot57/2\cdot30)}$$
$$= 2\,055 \text{ watts (per cable)}$$

$$W_{c/d} \text{ (per mile)} = \frac{6\cdot28 \times (5\,280 \times 30\cdot5) \times 15\,000^2}{100 \times 10^{10} \times 2\cdot30 \times \log_{10}(5\cdot12/4\cdot12)}$$
$$= 795 \text{ watts (per cable)}$$

Total watts (per cable) = 3 835

Total per 30 miles of cable = 115 050

= 115 kW per cable.

Now,

$$\frac{115 \text{ kW} \times 6 \text{ (cables)}}{50\,000 \text{ kW}} = 1\cdot375 \text{ per cent loss in 30 miles.}$$

Note.—The figure 100×10^{10} ohms per cm^3 is too low, and 150×10^{10} ohms per cm^3 is more nearly correct.

Comparing this now with the resistivity loss in the 30 000-volt three-core non-concentric cable, we have the following:—

$$\text{Watts per mile} = \frac{2\pi \times E^2 \times (5\,280 \times 30\cdot5)}{\rho_{(av.)} \times 2\cdot3 \times \log_{10}(1\cdot80/1\cdot20)}$$
$$= \frac{6\cdot28 \times (17\,320)^2 \times 5\,280 \times 30\cdot5}{100 \times 10^{10} \times 2\cdot3 \times \log_{10}(1\cdot80/1\cdot20)}$$

Watts per mile per core = 750
Watts per mile per cable = 2 250
Kilowatts per mile per cable = 2·25
Kilowatts per mile (10 cables) = 22·5
Total kilowatts in 30 miles = 675

Hence the percentage loss = 675/50 000 = 1·12 per cent. Hence the difference in leakage conductance loss between the 30 000-volt cable system and the author's 100 000-volt cable system is only one-quarter of 1 per cent.

Preliminary Calculations for Potential-drops on the Author's System.

The calculations may be greatly simplified—though of course with some loss of accuracy—by assuming that the reactance drop in the line at full load is of the same order as that worked out in Appendix B for a plain single-core cable (per phase), and that the capacity rise at no load is also of about the same order; also that the capacity current required for charging the further half of the line is fed to the substation through the central cores at 100 000 volts, in the manner indicated in Figs. 12 and 14.

We have then merely to see that the copper in the central cores is sufficient to carry the vectorial sum of the charging and load currents at a current density comparable with that obtaining for the load current alone; so that the drops in the two cases (i.e. with and without the load current) remain equal.

Having obtained the drop with the reduced section of copper and without the charging current (i.e. when carrying the "load" current alone), we can add the reactance drop and the capacity rise, taking these at the values given in Appendix B for a plain single-core cable, per phase. The sum of the three terms will represent the "regulation" of the line.

Assuming, then, for the present, that the whole load to be transmitted is divided, half being carried by the three "hexagons" and half by the "major star" (or stars) it will be found that the following is the division of the load current:—

(1) On the cores a and a_1 [see Fig. 9 (I)] we have to pass 152 amperes per core, viz. 90 amperes due to the "major star" and 62 amperes due to the "hexagon."

(2) On the cores b and b_1 and c and c_1 we have to pass only 62 amperes.

Let the central cores a, a_1 be worked at a current density of 750 amperes per square inch; let b, b_1 be worked at 560 amperes per square inch; and let c, c_1 be worked at 750 amperes per square inch.

The voltage-drops in any single wire are then: in a or a_1 1 125 volts; in b or b_1 843 volts; and in c or c_1 1 125 volts.

Expressed as percentage losses these are:—

a and a_1 = 1·95 per cent in terms of the "major star,"
= 3·75 per cent in terms of the "hexagons,"
b and b_1 = 2·8 per cent in terms of the "hexagons,"
c and c_1 = 3·75 per cent in terms of the "hexagons."

The cross-sections are :—

a and a_1 = 0·203 square inch, each (corrected to 0·235) (see below)
b and b_1 = 0·107 square inch, each
c and c_1 = 0·08 square inch, each.

The mean drop on the hexagons = (3·75+2·8+3·75)/3,
= 3·43 per cent.
The mean drop on the major star and on the hexagons combined = (1·95 + 3·43)/2,
= 2·69 per cent.

This means that at half load (at which point the major star is switched out) the major star at the receiving end would receive :—

$$100 - \tfrac{1}{2}(1\cdot95) = 100 - 0\cdot97 = 99\cdot03 \text{ per cent}$$

of the full voltage of the sending transformer; while the hexagon would receive 100 − ½(3·43) = 98·3 per cent of the voltage of the sending transformer.

The difference between them would thus be 0·7 per cent. This difficulty would be remedied by arranging for different winding ratios at the sending and receiving ends, so as to equalize the percentage drops at, say, three-quarter load, and so that on full load the major star would take too much load and at half load the hexagon would take too much. It might be desirable to have an automatic induction regulator with a very small range, but this is not at present contemplated.

Allowing for the capacity current of the system we must increase the section of the central core in the proportion of $\sqrt{[(152)^2 + (88\cdot5)^2]}/152$, i.e. to 0·235 square inch.

Allowing for this, and remembering that, on the occasion of the breakdown of a cable, the "hexagon" belonging to that cable is broken up and that consequently a proportion of the cross-section of the central core corresponding to 62 amperes is liberated and also that 62 amperes is liberated in the intermediate and external cores of the cable, it will be seen that the cable will readily be able to grapple with the situation if the cross-section of the central core be raised to the above figure.

This is substantially the figure that has been the basis of estimates of cost obtained from the cable makers.

The loss in transmission at full load, when averaged over the "major star" and the "hexagons," comes out, as already indicated, at 2·69 per cent.

If to this we add the capacity rise and reactance drop obtained previously (see Appendix B) for a single-core cable, viz. 1·2 per cent and 1·2 per cent respectively, we obtain a total of 5·1 per cent.

It must be remembered that, if the author's deductions are correct as to the practicability of supplying the charging current of the line from the lagging component of the consumers' load, both these "drops" disappear altogether, and the "regulation" of the line then becomes 2·69 per cent, a figure so low that we could afford to reduce greatly—perhaps even to halve—the cross-section of copper in the line, or, alternatively, to double the distance for the same "regulation" as that obtained with a single-core cable system.

We might thus easily transmit up to 50 miles with high efficiency, which means 100 miles when transmitting from both directions, as would be probable in railway work (e.g. between London and Birmingham).

APPENDIX E.

Comparative Costs of 30 000-volt and 100 000-volt Schemes.

Scheme "A" (30 000 Volts).

		£
Buildings		10 000
Oil switches (including busbars) :		
6 three-phase automatic switches, 5 000 volts, each to carry 2 420 amperes and rupture 1 500 000 kVA	£ 16 000	
6 three-phase non-automatic switches, 30 000 volts, each to carry and rupture 366 amperes	£ 10 000	
		26 000
Transformers :		
30 4 200-kVA, single-phase, 30 000-volt, 0·8 power factor, 50-period transfomers (including 2 spares)		60 000
Station cables and busbars, etc. :		
Allow		3 000
Trunk cables :	£	
Including laying	950 000	
Excavating and reinstating streets	50 000	
		1 000 000
Total		£1 099 000

Scheme "B" (100 000 Volts).

Buildings :		£
(Based upon actual figures)		25 000
Oil switches :		
5 000 volts.		
2 three-phase automatic switches, each to carry 3 340 amperes and rupture 1 500 000 kVA	£ 5 000	
6 three-phase automatic switches, each to carry 577 amperes and rupture 750 000 kVA	6 000	
4 three-phase automatic switches, each to carry 805 amperes and rupture 750 000 kVA	4 000	
100 000 volts.		
4 three-phase non-automatic switches, each to carry and interrupt 90 amperes	7 000	
12 isolating switches, for 200 amperes; 24 isolating switches, for 100 amperes	5 000	
3 earthing switches and isolating switches	2 000	
Sundries	1 000	
		30 000
"Major star" transformers :		
8 7 000-kVA, single-phase, 5 000/60 000-volt, 0·7 power factor, transformers. 8 7 000-kVA, single-phase, 2 800/60 000-volt, 0·7 power factor, transformers ..		52 800

			£
Brought forward			107 800
"Hexagon" transformers:			
20 5 000-kVA, 2 800/60 000-volt, 0·7 power factor, single-phase transformers	£	50 000	
6 2 500-kVA, 2 800/30 000-volt, single-phase, transformers ..		10 000	
			60 000

Note.—If the substation load be used to feed the capacity current, the above transformer cost will be reduced to, say, £75 000.

Station cables, busbars, etc.:	
Allow	5 000
Trunk cables	400 000
TOTAL	£572 800

Note.—If the substation load be used to feed the capacity current, the above total cost will be reduced to £535 000.

APPENDIX F.

The author desires to add the following interesting and, as he judges, important results obtained by Messrs. Clark and Shanklin in connection with the drop in the resistivity of the dielectric as affected by temperature, voltage gradient and frequency. The following figures are taken from some curves plotted by the author and roughly embodying Messrs. Clark and Shanklin's tests:—

Frequency	Voltage	Cable No.	Potential gradient	Temperature	Resistivity
∾	V		kV/cm	°C.	
60	12 000	2	15·8	24	185×10^{10}
60	12 000	2	15·8	30	120×10^{10}
60	12 000	2	15·8	40	53×10^{10}
60	12,000	2	15·8	50	27×10^{10}
60	12 000	2	15·8	60	12×10^{10}
60	12 000	2	15·8	70	8×10^{10}
60	12 000	2	15·8	80	5×10^{10}
60	12 000	2	15·8	90	4×10^{10}
60	12 000	2	15·8	100	$2·5 \times 10^{10}$
60	48 000	1	60	23	$38·5 \times 10^{10}$
60	48 000	1	60	30	25×10^{10}
60	48 000	1	60	40	15×10^{10}
60	48 000	1	60	50	9×10^{10}
60	48 000	1	60	60	5×10^{10}
60	48 000	1	60	80	3×10^{10}

Note.—Cable No. 1 had a core radius of 1·5 cm and an insulation radius of 2·53 cm.

Cable No. 2 had a core radius of 1·65 cm and an insulation radius of 2·61 cm.

APPENDIX G.

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Report of the Standards Committee of the American Institute of Electrical Engineers, June 1922: "Rating of Cables in Relation to Voltage."

Discussion before The Institution, 7 December, 1922.

Mr. C. P. Sparks: The problem put before us is the straight transmission of 50 000 kW over 30 miles, and the author gives a particular instance of transmission at 30 000 volts with three-core cables versus single-core cables with intersheaths at 100 000 volts. Straight transmission is, as a rule, to make use of natural resources, e.g. water power, or some form of fuel that cannot be transported. In this country we have particularly before us distribution over a wide area, i.e. the building up of a load sufficiently large to justify the use of large power stations, and such distribution requires a system suitable for control at a number of substations. The alternative method of transmission, viz. by means of overhead lines, is not mentioned in the paper, and I feel that straight transmission would have to be carried out by such means rather than by the three-core or the single-core cable proposed. Continuous improvement has been and is being made in cable design. The first 10 000-volt cables were designed by Ferranti and put into use in 1890, the dielectric having a thickness of ½ inch. The next definite step forward was between 1902 and 1903, when a system working at 20 000 volts came into use on the North-East Coast. In 1915 30 000-volt three-core cables were used for transmission in this country, amongst other instances being work carried out by me in South Wales. I expect the discussion will bring out the fact that cable makers are now prepared to build three-core cables and guarantee them not only for 40 000 volts but for still higher pressures. The limiting factor in connection with three-core cables is hysteresis, which was first drawn attention to by Mr. Mordey in 1901 in connection with certain tests which he carried out with me. It was then found that, with the lower pressures of 6 000 and 10 000 volts then in use, hysteresis in cables was unimportant. The question did not arise again until 1915, when the higher pressure of 30 000 volts was adopted. During the past five years cable makers have halved these losses, and at Birmingham the 33 000-volt cables have the same thickness of dielectric as was employed in 1890 for 10 000 volts, i.e. ½ inch. I feel that if the problem of straight transmission at 40 000 volts were before us, it could be solved by the use of five 40 000-volt, three-core cables at half the cost which the author has given for the 30 000-volt cables, without exceeding the practical limits of pressure loss in transmission. As a practical engineer, I require the cable to be armoured. The author says on page 221, "By increasing the amount of copper by 10 per cent, the iron wire loss can probably be compensated for by the reduced copper voltage-drop, and may then be neglected altogether." I want something much more reassuring than that, as I do not consider that it would be wise, from the point of view either of operation or of the safety of the public, to have cables working at the pressure suggested, unless the cables are armoured. On page 230 the author states that with 30 000-volt transmission the loss in transmission with 5 cables would be about 19 per cent, "and the latter regulation is entirely impracticable without a very great outlay in induction regulators and considerable expense in the maintenance of the same." With long lines I think a regulator is entirely justified. It is true that in short transmissions the expense is unwarranted, but I see no reason why, with our present knowledge of regulators, they should not be quite practicable on quite a large scale from the points of view of capital cost, running cost and reliability. In conclusion I feel that where straight transmission is required over a long distance, it should be effected by overhead lines. If, on the other hand, this is not practicable, then three-core armoured cables should be used at 40 000 volts or over.

Dr. J. A. Fleming: It is certain that if the electrification of main-line railways is to take place, the subject of transmission at high pressures by underground cables will have to be considered. The problem is fundamentally one of electric strength versus dielectric coefficient or constant. Unfortunately, these two qualities vary, generally speaking, in the same direction. An insulator of high electric strength has, with one exception, a high dielectric constant, the exception being compressed air. The electric strength of such material as is generally used in underground conductors, e.g. impregnated jute or hemp, is usually given at from 200 to 250 kV/cm. The dielectric constant is high, i.e. 3 or 3½; thus the capacity current is large. In the case of air, the electric strength at ordinary pressure is only about 30 kV/cm, but it increases almost proportionately to the pressure, so that if it is pumped up to 100 lb./sq. in. it will have an electric strength of about 200 kV/cm, i.e. approximately equal to that of impregnated jute or hemp. The important point is, however, that the dielectric constant will not increase much above unity, and therefore the capacity current will be about one-third of what it would be on a solid dielectric. Let us suppose that a copper rod is insulated by some suitable form of solid insulator in the axis of a copper tube as the return, and that the two are placed in a steel pipe which is jointed and made tight for a pressure of 150 lb./sq. in., the copper tubes being jointed by copper sleeves. If there were an air space of 1 inch all round the central conductor, the electric strength, at 100 lb./sq. in., should be 400 kV/cm, which would allow an ample margin, and there would be no difficulty in maintaining that pressure against a slight leak at a very small expense. Indeed, a small leak might be an advantage in keeping out moist air and in getting rid of ionized air. The one thing that might be questioned is whether the ionization of air would continue at 100 000 volts to an extent which would break down the insulation; also, whether there are any very serious difficulties in conveying the current through insulated glands into the conductors. I should like to see an experiment of that kind tried on rather a large scale, to find out whether with highly compressed air we could not derive the advantages of high electric strength with a small dielectric constant and, therefore, small capacity currents.

Mr. C. J. Beaver: The author has referred to the proposals which I made in 1915 with regard to these

intersheath single cables, but I should like to point out that those proposals did not originally emanate solely from me. Some of the suggestions with regard to the subject go back as far as 1906, when the general principle was suggested by Mr. Morris in connection with Dr. Russell's paper.* A considerable amount of work was subsequently done by Dr. Russell, Mr. Ll. B. Atkinson and Mr. A. E. Tanner in scientifically developing the principle of intersheath grading and adapting it to the conditions of commercial use. It has remained for the present author, by means of this six-phase/three-phase system, to combine the principle with a system of distribution in which intersheaths function as current-carrying layers as well as potential distributors. In taking that step he has enormously increased the commercial efficiency of the intersheath type of cable. Apart from questions of the operation of the six-phase/three-phase system, it seems to me that the author's proposals may be regarded as involving two sets of practical problems. The first relates to the production of the necessary transformers and switchgear, and the second to the manufacture and installation of the proposed cable. With regard to the latter, the author's demands on the cable maker in the matter of stress *qua* stress are not at all exorbitant, but the form of cable is somewhat foreign to present-day cable-making practice. I happen to know that the author has, or had, some misgivings as to whether the outer section of the cable shown in Fig. 6 could be made without endangering the efficiency of the inner portions by the heat treatment involved in the impregnation of the outer layer of dielectric. Such a danger undoubtedly exists in the ordinary vacuum or vacuum-pressure method of impregnation, but, as I have pointed out to the author, there is another method by which risks of this character can be entirely avoided. Broadly, this consists in impregnating the paper in sheet form prior to cutting it into strips and applying it to the conductor. This method was evolved by me in 1897, and has been solely used by my company ever since. Obviously, all parts of a dielectric made on this principle must receive the same treatment, whereas this cannot be the case in the ordinary method. Moreover, in the ordinary process the dielectric properties of the impregnating medium—in so far as they are correlated to physical properties—have to be subordinated to the necessity of penetrating the mass of paper under reasonable conditions of time and temperature. Having to be thin and mobile in order to penetrate, a tendency to bleed out again, or to become displaced under working temperature conditions, is entailed. In addition, there is always the risk of insufficient penetration on the one hand, or too prolonged exposure to the high temperature of the impregnating process on the other. The "prior" impregnating process is entirely free from these disadvantages, allows considerably greater freedom in the choice of materials, and consequently permits much more scope in securing the best combination of physical and electrical properties in the impregnating medium. The desirability of this method becomes, of course, greater as higher voltages and consequently greater thicknesses of dielectric have to be dealt with. The author's reference to the work of Clark and Shanklin and others brings up the important subject of the effect on dielectric losses of the occlusion of air and gases. These investigators attached so much importance to this matter as to conclude that the critical stress at which occluded air becomes ionized—about 19·5 kV/cm—should not be exceeded in an impregnated paper dielectric. British cable makers, however, did not accept this dictum, and to-day more than one firm, including my own, can point to cases of two years or more of satisfactory working at stresses up to 50 kV/cm. There appears to be little doubt, however, that freedom from occluded air and gases would give considerable advantage not only with regard to dielectric loss, but probably also to electric strength. The "prior" impregnation method gives freedom from occluded gases because there is no heat treatment after the dielectric is built up. With regard to occluded air, I do not think that either process has yet produced an absolutely air-free dielectric, although certain refinements are employed to that end in each. It will be fairly clear, however, on a moment's consideration, that if, in the "prior" method, the already impregnated paper strips could be applied to the cable in an air-free medium, e.g. under the surface of very viscous oil or molten compound, the dielectric so built up could not contain air. The necessary plant to accomplish this has been designed and constructed and will shortly be in use.

* "The Dielectric Strength of Insulating Materials, and the Grading of Cables," *Journal I.E.E.*, 1908, vol. 40, p. 6.

Mr. P. V. Hunter: It seems to me that, up to the present, cable manufacture and research and development on cables in this country have proceeded on quite fixed and well-defined lines. Certain definite forms of cable have been stereotyped, and the direction of progress has been to try to increase the specific loading of the materials. For instance, the question of the current density at which cables can be run has during the past 10 years received very considerable attention, and the stress at which the dielectric can be operated has received if anything even more attention. This has resulted in considerable progress, but in one direction only. Now the author has entirely ignored all this line of progress and has set himself quite different ideals. It would therefore be hardly fair to criticize the paper for not dealing with this aspect of development. I should like to say, however, that he has not done the cable manufacturer of this country anything like justice in the 33 000-volt cable which he has shown on page 232 for the purpose of comparison with his own proposals. It must be remembered that the author's proposal is, after all, very speculative. If, therefore, he has put up a speculative proposal he ought to compare it with something of a similarly advanced nature in existing methods, and I think I shall be quite safe in saying that a 66 000-volt three-core cable run at $2\frac{1}{2}$ times the current density that is proposed in the paper for the 33 000-volt cable would be a great deal less speculative than the cable and method of operation proposed by the author. Had he made his comparisons on this basis the saving of £500 000 would, of course, have completely disappeared. I think that the author's proposals really amount to this: "I will put a stop

to any attempts to increase the specific loading of my materials, and I will see whether by changing my circuit arrangements or by any kind of subterfuge I can gain advantages in other directions." He has no doubt been encouraged in this line of attack by the fact that in communication circuits there have been very great advances in dealing with the development in this way. Mr. Gill in his Inaugural Address told us how many long-distance communication circuits were operated on four wires. The number appears almost incredible to a power engineer unfamiliar with such matters, and I think that the present author has set himself to discover whether or not it is possible to arrive at some similar kind of development in power work. I do not think for a moment that the particular schemes which the author has proposed are in the slightest degree practicable. Mr. Sparks has pointed out that, as described, the scheme proposed would appear to be suitable only for straight end-to-end transmission. I do not think any scheme which is limited in that way would be at all applicable to the conditions of this country. On the other hand, if an attempt is made to apply this scheme to any kind of high-pressure interconnected distribution network, the amount of switching entailed will be excessive. For instance, the number of busbars required in a substation where there is a junction between three such feeders as are shown in Fig. 11 would, I think, be 21. To make the scheme at all practicable the serious difficulty of capacity current which the author has encountered has to be overcome. This difficulty is met with on all occasions when one tries to limit the maximum stress on the dielectric and employ it more usefully by running at a constant stress throughout. This means, in the case of single-core cables, or cables of similar construction, that the large mass of dielectric near the outer periphery has to have its stress increased. The result is a large increase in capacity current. The author's proposed scheme of neutralizing the capacity current and running at unity power factor should not be credited as an advantage of his system. It is an essential complication which must be adopted because he is running into the difficulty of greatly increased capacity current. As he has to attack this difficulty it is very natural that he should attempt to eliminate the capacity current entirely, and with this I agree. Fig. 11, I understand, gives in diagrammatic form the essence of the author's specific proposals. I am not sure that it is easy to follow from the description what is intended and the reasons which have led the author to the arrangement shown, and it may be of interest to state briefly the genesis of the arrangement as it appears to me. The author has chosen a main transmission pressure so high that some form of single-core cable is necessary. In order to keep the dielectric stress within the limits postulated he has had to assume the use of intersheaths regulating the pressures between sections of the dielectric. These intersheaths must necessarily carry large capacity currents and, with a view to increasing the amount of energy transmitted by the arrangement, and also no doubt having in mind that the addition of capacity currents and energy currents gives a resultant of less magnitude than the arithmetical sum, he has endeavoured to arrange that the intersheath shall also carry energy current. It would be almost ideal for his purpose if the energy current to be carried by the intersheaths could have been the ordinary three-phase system, but unfortunately this is not very suitable. The result has been that the author has had to employ a six-phase arrangement for superimposing on his intersheaths, and this has led to the employment not only of the hexagon arrangement but also of six cables instead of three, which would otherwise have been satisfactory. On the whole, therefore, it is fair to state that the main object of the whole of the arrangement is to employ intersheaths for the purpose of transmitting energy, as well as capacity currents.

Communicated: It is well that attention should be directed to the author's argument for employing an excess of cables in order to save energy losses. The author computes that a 1 per cent saving in energy lost is equivalent to £58 300 in capital expenditure. The cost of a unit of losses is assumed to be 0·5d., the period on which the computation is based being 16 years. This computation obviously assumes that for the next 16 years there will be no reduction in the cost of producing electricity, which seems to me to be very improbable indeed. If, however, there is a reduction in the cost of producing electricity, then the capital value of the losses falls, and I have no hesitation in predicting that during the next 16 years the cost of the losses will be very substantially less than the figure stated by the author, with the result that any capital expended on the assumption that it paid to spend capital to save losses would be largely wasted. Apart, however, from this weakness in the author's argument, the whole suggestion that supply authorities should spend capital purely for the purpose of saving losses is against all commercial practice. In the author's case he proposes to run his 33 000-volt cable at a current density of 500 amperes per sq. in., when a density of at least 1 250 amperes per sq. in. would be permissible. In other words, although four cables would be sufficient for his purpose he proposes to put in ten, merely because he can show on paper that the saving in losses would justify the extra capital expenditure. This argument seems to me to find no support in practice in this or any other country, nor is it likely to appeal to any branch of the industry with the possible exception of that which makes the cables.

Mr. J. S. Highfield: A study of the paper seems to suggest that the author is adding to the well-known complication of transmitting electricity by alternating currents; and it makes one feel all the more that if, for the sake of simplicity, we could generate and transform direct current, the whole problem would become much more simple. On that subject the author suggests that even if we could use direct current there would still be this difficulty of intersheaths in order to make the insulation secure. I can assure him that up to 100 000 volts there is no difficulty at all in using a single-core cable with ½ in. of insulation (or perhaps a little more) to work at 100 000 volts. For some years there has been a cable supplying Lyons at that pressure. I laid a main consisting of two single-core cables of 0·125 sq. in. cores plain lead-covered and laid in iron pipes, for the Metropolitan Electric Supply Company,

to work at 100 000 volts. Dr. Fleming has referred to the use of compressed air as an insulator. He may be interested to hear that some years ago, when I was working a great deal on the possible use of direct current for high-tension transmission, it became obvious that it was much easier to make a compressed-air cable with one core than with three. With one core it appeared to be sufficiently easy to be worth trying. In fact we laid down a good many lengths of 18 ft. steel tube with an insulator on each joint, and drew through these insulators a stranded cable of about $\frac{1}{4}$ sq. in. section. We drew it up tight so that it could not touch the tubes. It was quite easy to go round corners because there was a suitable insulator at each joint. Working at a pressure from 100 to 120 lb./sq. in. there was no difficulty in applying an alternating current of 60 000 volts between the conductors and the outside of the tube, the diameter of which was, I think, 4 in. In common with Mr. Hunter, I have experienced some difficulty in understanding in what the proposed new system consists, and I do not quite agree with Mr. Hunter's interpretation. Mr. Hunter has discussed Fig. 11 as though an essential part of the system were six cables and a large bunch of transformers. I think that the author could carry out his system perfectly well with one three-phase/six-phase transformer and two three-core concentric cables. His connections are, I think, designed with the idea of keeping two of the neighbouring phases as near earth potential as possible, i.e. about 15 000 volts; the two highest phases within about 90 000 volts; and the two middle ones within about 60 000 volts. Consequently the system might consist in a single transformer providing six phases and two three-core concentric cables.

Mr. P. Dunsheath: There are many points in the paper with which I either do not agree or on which I am unable to follow the author's argument. I think that in dealing with certain fundamental principles the author has made one or two slips. One matter to which I should like to call particular attention appears on page 223. Assuming the power factor of the dielectric to be 1·5 per cent, the author calculates the dielectric losses in the usual way, but calls them hysteresis losses, and shows them as hysteresis losses in Fig. 3. That, in my opinion, is not correct. The product of power factor, pressure and charging current gives the total dielectric loss including the conductance losses, which the author refers to as a separate item in the lower part of col. 1, page 223. Turning now to the author's six-phase/three-phase system, apparently he employs six cables as detailed in Fig. 6, and by applying 30 000 volts between the inner conductor and the first intersheath, another 30 000 volts between the first and second intersheath, and 18 000 volts between the latter and the lead, he is able to work a 100 000-volt three-phase system. It seems to me that the best way to criticize the system is to compare it with a straightforward tapping system, using exactly the same cable with the same voltage between conductors. In Fig. A I have shown the elements of the author's system on the left-hand side and the equivalent simple tapping system on the right-hand side. It is obvious from the vector diagram that the addition of the vector voltages is considerably less with the author's system than with the simple tapping system. As a matter of fact, with equal stresses on the dielectrics of two equal-sized cables the voltage available on the left-hand system is 58 000 and on the right-hand system 78 000. It seems to me that this is really the basic principle of the matter, and to condense my point I should like to ask the author what are the

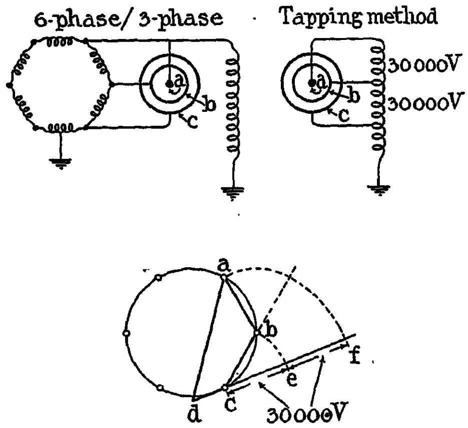

FIG. A.

advantages of his system over that shown in Fig. B. Here two, four or six cables constructed similarly to that of Fig. 6, *but only up to the first lead sheath*, i.e. 4·02 cm radius, are used instead of an equal number of cables in accordance with Fig. 6, with a radius of 5·12 cm. With the alternative which I propose, six cables, much smaller than the author's, will carry the

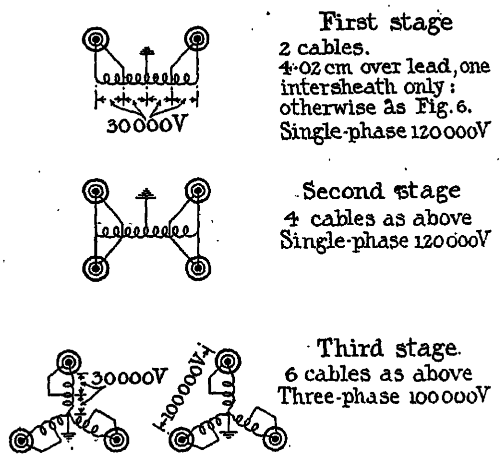

FIG. B.

same voltage, i.e. 100 000 volts three phase, without the complication of any six-phase hexagons and without the loss, so far as I can see, of a single advantage claimed for the six-phase system. On the question of carrying load current in the intersheaths, the author implies that this is one of the advantages of his system. Now this advantage can be claimed for any intersheath system, but is it such an advantage, after all? At first sight it seems to be a very attractive proposition,

but when it is remembered that energy carried at the top voltage in the main conductor requires much less current than if carried in an intersheath, the advantages are not so obvious. In passing, I should like to state that the author is not the first to propose the use of intersheaths for carrying current. The firm with which I am connected hold a patent * for doing the same thing on a simple tapping system. So far my criticism has been of the author's method of using intersheaths, but I should like to say a word on intersheaths in general. The development of super-pressure cables by the use of graded potential intersheaths has been very much discussed, but I do not think they are as effective as they are generally considered to be. I know that many authorities hold that a cable breaks down at a certain maximum stress and that, by a re-distribution of stress by potential sheaths, higher values will be obtained for the breakdown of a given total thickness of dielectric. I am sure that when we know more about this subject we shall find this to be absolutely untrue.

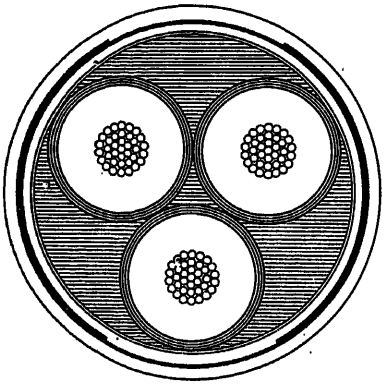

FIG. C.—"S.L." type of 60 000-volt, three-core cable. Conductor 0·23 sq. in. (37/0·090); overall diameter 4·5 in. (Henley).

A cable does not break down when a certain maximum stress is reached, but for some other reason. I know that makers of condenser-type terminals are quite convinced of the usefulness of intersheaths, but I am of the opinion that if intersheaths do improve a dielectric they do so by re-distributing the heat, and possibly stress, circumferentially rather than by re-distributing the stress radially, and that if an intersheath cable were left without the ends connected to transformer tappings the results would be quite as good as if they were connected. It is largely because of these views on the uselessness of potential grading that I have been working during the past few years along the lines of developing super-pressure cables, using three-core cables, and I find that it is practicable to transmit the power required for the case quoted by the author, i.e. 50 000 kW, over three three-core cables having an overall diameter of 4·5 inches. The cable may be either plain three-core or of the type which I prefer, shown in Fig. C, which I will refer to as the S.L. type, as the cores are each separately lead-covered. The objection to the use of single-core cables is very frequently based on the impossibility of armouring, but here is a type in which the armouring is easily employed and which has many other advantages, both mechanical and electrical. As it may be objected against my suggested alternative to the author's system that the losses will be more, I have tabulated various values, from which it will be seen that the advantage is all with the three-core type. The S.L. type has somewhat larger losses than the plain three-core cable, but its many other advantages, e.g. flexibility, uniformity of temperature, etc., more than compensate for these. As regards cost, I estimate that the saving of £500 000 shown by the author by using his system could be increased to about £550 000 by using three three-core cables as suggested. The figures in the following table are obtained from a long series of tests recently carried out and still in progress on two lengths of 60 000-volt, three-core cables, samples of which I have placed on the table for inspection.

* British Patent 138 377.

Comparison of Six-phase/Three-phase Transmission at 100 kV *with Simple Three-phase Transmission at* 60 kV.

	6-phase/3-phase: 100 kV	Simple 3-phase: 60 kV	
	Using 6 concentric cables	Using 3 plain 3-core cables	Using 3 S.L. type 3-core cables
Distance ..	30 miles	30 miles	30 miles
Regulation ..	5 %	5 %	5 %
Charging kVA per phase	20 460	8 750	10 300
Copper losses at full load, in kW	1 387	2 023	2 023
Sheath losses at full load, in kW	? (take = 0)	? (take = 0)	202
Copper and sheath losses, in kW	1 387	2 023	2 225
Ditto per annum, in units, 40% load factor	1 940 000	2 840 000	3 120 000
Dielectric loss at full load, in kW	918	394	463
Dielectric loss per annum in units, 24 hours' load	8 050 000	3 460 000	4 060 000
Total loss per annum, in units	9 990 000	6 300 000	7 180 000

Dr. W. Cramp: In the first place, the use of single-core, lead-covered cables for alternating currents is, to my mind, now a thing of absolute certainty. It is perfectly safe to use them even for periodicities higher than 50. I am in possession of figures which show that the loss which the author has allowed in the lead is really in excess of what he is likely to meet with in practice. I would go further and reassure

Mr. Sparks to this extent—that experiments which are now being carried out at Birmingham seem to show that even in a single-core *armoured* cable the loss is much less than is generally anticipated. The second point is that cable makers who have used intersheaths, and who propose to use them, seem to me to be omitting one important theoretical possibility. It is well-known that if a conductor and a partial conductor carry a current such as this capacity current, a charge will collect at the junction between them, and will disappear directly the current disappears. If the capacity current has to pass through the metal sheath—that is to say, if the current on the two sides is virtually the same, so that the capacity current travels from core to core—there will be a charge on each side of the metal sheath, and it may be of very considerable magnitude, in fact sufficient, if there are spaces between the wires, as in the author's rings, to set up an ozonizing discharge. In any case there is the possibility of breakdown near an intersheath due to that cause.

Mr. A. M. Taylor (*in reply*): It would seem to be true that, as the *Electrician* remarks, I have not done myself justice in the presentation of the facts which are enunciated in the paper. I will try to remedy this in the reply to the discussion.

The essential points which can be deduced from the data given and on which the paper will stand or fall are the following:—

(1) By employing intersheaths in the manner outlined a gain of roughly 100 per cent in the voltage applied can be obtained for a given depth of insulation.

(2) This enables either the current density in the central copper core to be kept constant while the core section is halved, or alternatively (and this is what I use in my calculations later) the current density to be doubled while the cross-section is reduced to one-quarter.

In the first case half the heat is liberated per foot of cable, and consequently, for two single-core cables of similar thermal constants (one at 55 000 V, non-intersheathed, and the other at 110 000 V, intersheathed) the thermal gradient is halved, i.e. the temperature-rise of the copper is halved.

(3) In the transition from a three-core non-intersheathed cable to a single-core intersheathed cable there is a gain in the thermal gradient—i.e. a reduction in the copper-core temperature-rise—of some 60 per cent, due largely to there being the heat losses of three cores concentrated in the one cable, and in the other that of one core only.

(4) The resistivity gain, due to the reduced temperature of the central core, would of itself be very valuable; but in the case of intersheath cables worked under my proposals the additional gain, due to putting those parts of the dielectric which have to work under the highest dielectric stress at a part of the cable where the temperature is lowest, is very great and would amply compensate for any moderate loss due to increased capacity current. Incidentally, it should also permit of working at much higher voltage gradients, and hence of still further increasing the transmission voltage.

(5) By the method of working proposed, the capacity current at light loads is reduced to one-third of that at full load.

(6) The increase in the total capacity from core to lead sheath (apart from temperature questions), due to the introduction of intersheaths and consequent slight increase in diameter of cable, is almost negligible. In a case which I have worked out it is only 5 per cent.

(7) Above a certain temperature, easily reached in practice, the "leakage conductance loss" (which depends directly on the resistivity) increases very rapidly and outweighs the loss due to increased "permittivity" (i.e. the extra capacity current loss), besides ultimately causing the breakdown of the cable.

In view of the fact that, in the near future, transmissions of a magnitude now only hinted at will certainly be undertaken, and that it is impossible to keep on indefinitely increasing the potential gradient in three-core cables to meet the new conditions, it is advisable—and will assist true progress meanwhile—to consider *now* how these transmissions are to be undertaken. The present paper was written with this object.

Replying now in detail to the discussion on the paper, the most serious criticism is, I take it, that the work can equally efficiently be done with, say, five 55 000-V three-core cables. But those who make this criticism have surely overlooked the supreme importance of temperature considerations. E.H.T. trunk cables may, in emergency, be called upon to carry loads far in excess of their normal loading, and this may occur in the summer time. To neglect this possibility would be suicidal. It is also surely of some importance that an unnecessary £50 000 to £75 000 should not be incurred in regulators, which lose (in boosting by some 20 per cent) from ½ per cent to perhaps ¾ per cent of the whole power of the system. I propose to attack the problem from the point of view of temperature of the dielectric. It is rather interesting that the latest important contributor to this question, Dr. Karl Willy Wagner,* emphasizes the drop in resistivity due to temperature as being of supreme importance and the probable initial cause of all breakdowns. The curves which I exhibited as a lantern slide show most conclusively the importance of this question of the leakage conductance loss; also, how remarkably the resistivity itself, for a given ambient temperature, depends on the potential gradient. In the paper I have done my own proposals an injustice by designing a cable such that the present methods of impregnation could be applied to it. As, however, there is a reasonable probability of our being able almost immediately to obtain cables in which (apart from the question of bending, which can be dealt with by larger drums and other precautions) it is immaterial whether the maximum potential gradient occurs at the surface of the central core or on one of the intersheaths, I will take advantage of the gains which my proposals really involve, were such a cable immediately forthcoming. Even if, however, I had to fall back on the cable shown in Fig. 6 of the paper, my conclusions would not be seriously affected.

* *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 1034.

A careful examination of Tables 2 and 3 will show that, for practically no more loss than in Table 2, an advantage of 50 per cent in the maximum potential gradient applied to the innermost core (i.e. the hottest —at time of full load) is obtained, as compared with the gradient of Table 2; also that, in Table 2 itself, an advantage of 47 per cent over Table 1 (ordinary non-intersheath) is obtained in the E.M.F. absorbed for a given thickness of dielectric. An advantage of $1 \cdot 47 \times 1 \cdot 50 = 2 \cdot 2$ is thus obtained in the E.M.F. that can be applied to an intersheath cable, for an equal thickness of dielectric—i.e. we may apply 2·2 times the E.M.F. of transmission for a given maximum potential gradient next the central core. Unfortunately, however, this has, in the six-phase/three-phase system, to be discounted by 15 per cent on account of the obliquity of vectors. This brings the gain down to $2 \cdot 2 \times 0 \cdot 85 = 1 \cdot 87$ times; which, however, is only 6½ per cent short of twice. In view of the fact that I am going to compare a 55 000-V three-core non-concentric cable with a single-core 110 000-V intersheath cable having nearly an inch less diameter under the lead sheath (representing a "gift" of very much more than the aforesaid 6½ per cent) it will doubtless be conceded as reasonable that, for a round figure, the above gain in voltage be taken as 100 per cent—not to mention further gains which I might have drawn upon. The three-core cable chosen for the purpose of examining thermal gradient is a standard cable having 1·25 cm thickness of insulation both on conductor and on belt and measuring 10·9 cm over the insulation, in which the maximum potential gradient is 40 kV/cm, the cross-section per core being 0·15 sq. in. The maximum potential gradient is calculated according to Atkinson's method,* which, I believe, is generally accepted as being more accurate than the ordinary method. The internal diameter of the lead sheath is 10·9 cm, as compared with 8·2 cm † for the single-core cable. Had the larger diameter been reduced to 8·2 cm the effect on the maximum voltage gradient of the 55 000-V cable would have been very serious.

Prior to giving detailed consideration to the three-core non-concentric cable, let us first compare two single-core cables—one (intersheathed) for 110 000 V and one (plain) for 55 000 V. It has just been shown that the voltage may be doubled for equal thickness of insulation where intersheaths are employed (single-core cables being considered); let us, then, examine what the doubling of the voltage gives us and, for the sake of simplicity, ignore capacity current:—

(1) Half the load current is required.
(2) The percentage drop may be kept constant.
(3) The copper cross-section per phase (in the 110 000-V cable) is reduced to one-quarter.
(4) The current density is doubled.

Now, to fix ideas, take the 110 000-V cable of Fig. 1 of the paper, of which the cross-section of copper is 0·185 sq. in. The cross-section per phase (2 cables are in parallel per phase; see Appendix B) = 0·37 sq. in. Hence:—

(5) Copper section per phase on 55 000-V cable $= 0 \cdot 37$ sq. in. $\times 4$ (as deduced above) $= 1 \cdot 48$ sq. in.

(6) No. of cores required in parallel $= \dfrac{1 \cdot 48 \text{ sq. in.}}{0 \cdot 15 \text{ sq. in.}}$ (see Note below)
= 10 cores (per phase).
= 30 single-core cables (per 3 phases).

Note.—We cannot put more than 0·15 sq. in. into the three-core cable about to be considered without exceeding the potential gradient of 40 kV/cm.

Now consider that these 30 cables are to be replaced by 10 three-core (55 000 V) cables, and compare the heating in the two cases.

The total heat generated per phase in the 110 000-V cables is obtained as follows, bearing in mind that 2 cables are in parallel per phase on the 110 000-V system, and 10 cables on the 55 000-V system. It is simpler to compare 5 cables of one system with the one cable of the other system; so let us work it out this way:—

The current density on the one 0·185 sq. in. cable works out at approximately 1 000 A per sq. in. (see Appendix B). Hence, from the conclusion already arrived at,

Current density in 55 000-V 0·15 sq. in. cable = 500 A per sq. in.

Now

1 (50 000 V) core at 500 A per sq. in. and of 0·15 sq. in. section represents X watts per ft.

also

1 (110 000 V) core at 1 000 A per sq. in. and of 0·185 sq. in. section represents $4X \times \dfrac{0 \cdot 1}{0 \cdot 150}$ watts per ft.

and

3 (50 000 V) cores at 500 A per sq. in., each of 0·15 sq. in. section, represent $3X$ watts per ft.

But the thermal resistance of the 0·15 sq. in. three-core cable is 95·5 and that of the 0·185 sq. in. single-core cable is 82·5.

(The above thermal resistances are as determined by well-accepted methods.)

Hence the thermal gradient of the 110 000-V cable in terms of the 55 000-V cable is:

$$\frac{4}{3} \times \frac{0 \cdot 185}{0 \cdot 150} \times \frac{82 \cdot 5}{95 \cdot 0} = 1 \cdot 42 \text{ times.}$$

This, however, is for 10 cables in parallel and for 500 A per sq. in.

If we work at higher current densities and with fewer cables in parallel (and greater percentage loss) we get the following results:—

The 110 000-V cable is 1·42 times hotter, when we have ten 0·15 sq. in. three-core cables.
The 110 000-V cable is 0·91 times as hot, when we have eight 0·15 sq. in. three-core cables.

* *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 971.
† Based on Fig 1, but modified for 40 000 V/cm.

The 110 000-V cable is 0·51 times as hot, when we have six 0·15 sq. in. three-core cables.
The 110 000-V cable is 0·22 times as hot, when we have four 0·15 sq. in. three-core cables.

So that, with even 8 cables, there is a gain of 9 per cent to be credited to the single-core intersheathed scheme, neglecting altogether the additional advantage that the dissipation of part of the (copper) heat nearer to the outside of the cable gives us. It may be pointed out that an easy calculation shows that the effect of adding intersheaths to a non-intersheath cable is to reduce the thermal gradient (in the proportion of 78·9/82·5 in the case of Fig. 1) rather than increase it, as one might possibly imagine. If only 4 cables were chosen (equivalent to Mr. Sparks's 5 cables at 40 000 V) the 2·5 per cent line drop taken in Appendix B becomes 5·0 per cent, involving 2½ per cent additional loss in the 55 000-V scheme, which, as I have shown elsewhere, is equivalent to £194 000 when capitalized; *besides the fact that the innermost insulation is no less than 4 times hotter;* which factors must work to the ultimate destruction of the cable.*

It only remains to add that my calculations are all on a common basis as regards maximum potential gradient. Mr. Dunsheath's figures, and probably also Mr. Hunter's, are vitiated by the fact that they are based on 50 000 V/cm; just 25 per cent more than mine. It may therefore be taken that 8 cables are necessary for 50 000 kW and 16 cables for 100 000 kW against 6 cables with the six-phase/three-phase system, a saving of 10 cables in the latter case (or, say, £750 000).

Before leaving the subject of the number of cables it is as well to remark that all my comparisons in the paper are on the basis of maximum potential gradient. I am quite familiar with the fact that this has been challenged as a criterion of the breakdown strength, and I have carefully followed all that has been written on the subject during the last 2 years. As far as I can judge, Mr. D. M. Simons's paper before the American Institute of Electrical Engineers † is the most complete investigation on the subject and his conclusion that, although the maximum potential gradient may not determine the immediate breakdown of the insulation when under test, yet nevertheless it probably determines the ultimate breakdown after a lapse of time, is one with which I fully agree. Although no actual breakdown or deterioration of the insulation next to the central core may be visible on opening up the cable, yet it is undeniable that the atomic stresses must be greater where the potential gradient is greater (with greater hysteresis loss and consequent heating), and it is also undeniable that the potential gradients follow the laws predicated of them, in a uniform dielectric.

Mr. Hunter has challenged the soundness of paying too serious attention to the cost of energy wasted in the cable, and he suggests that the figure of 0·5d. (as an *average* figure) which I have taken for the cost of energy delivered, on only a 40 per cent load factor basis, at a substation 30 miles away, is too high. Surely Mr. Hunter must know that the official life of a high-tension cable is not 16 years, but 25 years; and if I were to reduce the above 0·5d. to 0·33d. (involving a *minimum* figure of 0·16d.) and still were to say that 1 per cent of lost energy meant £78 000, would he be sufficiently optimistic to say that 0·33d. was too high, considering the load factor and the point of delivery? Does he suggest that central station engineers are wrong when they consider carefully the last 1 per cent of the guaranteed efficiency of the plant in determining the tenders? Mr. Hunter is apparently very much alarmed by the amount of capacity current taken by my proposals, and the consequent energy wasted in dielectric loss. I may say at once that I anticipate that the capacity current will be some 80 per cent greater than with an ordinary type of three-core cable. The energy loss due to this will not, at the most, be more than an additional 0·8 per cent of the total power transmitted. Really the total loss will be *less than half the full-load loss,* because of my method of working the transformers and lines in sections. Perhaps he has overlooked the fact that at higher voltages one is bound to get greater capacity current than at low voltages, and if he can ever work up to 100 000 V with three-core cables he will find just the same troubles staring him in the face. I, on the other hand, am equally interested about the conductance losses in Mr. Hunter's cable, owing to the high temperatures of the dielectric, particularly in view of the calculations given on page 236, which show that, even assuming in both cases a comparatively cold dielectric, there is only a difference of 0·25 per cent between the loss with my cable at 100 000 V and a 30 000-V three-core cable. Had I made allowance for the hotter dielectric in his cable, the loss would probably have been much higher. The hotter dielectric, as already pointed out, also affects the permittivity, and consequently the capacity current. Mr. Hunter has arrived at the conclusion that my scheme is not in the slightest degree practicable. I submit that such a wholesale condemnation without any definite specification of the reason is unfair to the author. I presume that he condemns it on account of the alleged complexity of the transformer arrangements. This is merely because they are new to him, and, no doubt, in particular the superposed "major star" arrangement has frightened him. It may relieve Mr. Hunter's mind to know that the scheme can be equally well carried out, and the voltage of transmission still maintained, without any "major star" at all. The system then simply becomes, at the step-up end, three ordinary transformers having the secondaries coupled in double star, which is no more complicated than is used daily in conjunction with rotary converters. Fig. D shows these new conditions. As regards the alleged complexity of the switching, I do not propose to do any automatic switching on the high-tension side, and if possible no non-automatic, except at times of light load. I believe, from a careful study of the experiments carried out by Steinmetz and others, that we should be simply inviting trouble by having auto-

* Had the first case, alluded to at the commencement of this reply, been taken, the argument in favour of cooler cables could have been made very much stronger. In fact, the core temperature would have come out 10 *times* higher, with 4 cables, than with the 100 000-V system.

† *Journal of the American Institute of Electrical Engineers,* 1922, vol. 41, p. 433.

matic switching on the high-tension side with long lines of underground cables. Time will prove whether I am right or not in this prediction. With regard to the suggestion that I should not be allowed to credit my scheme with the neutralizing of the capacity current and running at unity power factor, I have already dealt with this at some length, and if Mr. Hunter will refer to the calculations for a single-core non-intersheath cable at 100 000 V, as given in Appendix B of the paper, and will compare them with the calculations for my own cable, given in Appendix D, he will find that the total kVA under the two schemes is almost identical, which is a sufficient answer to his statement that I have a "greatly" increased capacity current.

Mr. Sparks has implied that the cost of a five-cable transmission at 40 000 V would be only half that of

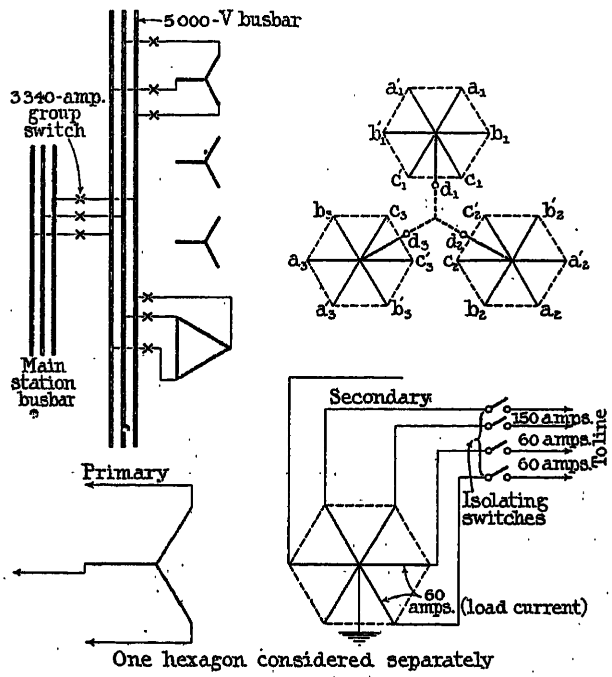

FIG. D.—Switchgear arrangement at sending station.

NOTE:—The dotted lines between points d_1, d_2 and d_3, represent conductors of no resistance.

the cables in the six-phase/three-phase system, and he must surely be very seriously in error. The prices given in Appendix E of the paper for ten 30 000-V cables were the results of estimates from several of the leading cable makers and were compared by me with prices of actual cables then in my possession.

Now the cost of a three-core 0·15 sq. in. cable for 55 000 V will not be appreciably less than that of a three-core 0·25 sq. in. 30 000-V cable, except for the value of the copper saved. (There will in fact be more lead, owing to the greater diameter consequent upon the higher insulation required.) The figures given for the latter cable, including joints and laying, were of the order of £95 000 per cable per 30 miles. Knocking off £12 000 for the reduced copper (including the profit on the same) the price reduces to £83 000 per cable. Now the price per multi-core concentric 100 000-V cable given in my table is only £66 000 per 30 miles, hence Mr. Sparks wants us to believe that his three-core 40 000-V cable will cost only £33 000 per 30 miles. There is a big jump between £83 000 and £33 000 and it is not likely that the cable makers, who simultaneously gave prices for the two systems and knew that they were going to be compared, would make out the worst case that they could for their normal construction of cable. On the question of armouring I can assure Mr. Sparks that the armouring of the cables can be dealt with for less energy than he proposes to lose in his regulators. I expect a great deal less from calculations based on Dr. Whitehead's experiments and Steinmetz's figures, and Dr. Cramp seems to be of the same opinion. As regards a "straight" transmission, I submit that in the ordinary course of things the 100 000 V would only be required for a point-to-point transmission, but that where tappings off such a line took place it would be quite practicable to step down to, say, 30 000 V (or lower) and to carry out ordinary three-phase distribution from the tap-point in each district; and the change from six-phase to three-phase is easy, simple and reliable. If, however, such a step-down is not required at the tapping point, a plain "connection substation," which would be quite cheap, could be used. Mr. Sparks gives it as his view that overhead transmissions will be largely employed for all point-to-point distribution over long distances in this country. I believe, on the contrary, that with the continued use and development of aviation on a big scale there will be great danger in fogs from aeroplanes colliding with overhead lines, in many cases bringing down the latter, not to mention disastrous results to those in the aeroplane. Moreover, the cost of overhead transmission is not at all so low as Mr. Sparks imagines. Where two lines of towers are required, which I suggest is only reasonable on very important transmissions, and upon which I believe even our American friends have decided for such transmissions, the difficulty in obtaining wayleaves for these lines of towers across country will be quite considerable, and some compensation will also be necessary for the strip of land between tower and tower which is threatened by falling wires. The cost per kVA per mile for a 100 000-kW transmission on the lines I am recommending would only be of the order of £0·18, and I remember not so long since analysing an important American estimate for overhead transmission in which (if my memory serves me right) it worked out to something like £0·2 per kVA per mile; so that on such a transmission the cost with underground cables would be as cheap as with overhead, and enormously more reliable.

With regard to Mr. Highfield's remarks, I gather that the area of the 100 000-volt d.c. main to which he alludes would be only 0·125 sq. in. and that the cable would really be working under only 50 000 volts between any part of the core and earth. It would be interesting to know whether this cable has ever been used to carry, say, 150 amperes in the hottest part of the year for several hours, or whether it is merely run at a low current density. No doubt Mr. Highfield is aware that it has been known for some time that, with cables in which

the ratio d/D is of the order of 0·3 (which obtains in the present case), values of the maximum potential gradient greatly exceeding standard values have been observed before breakdown occurs—I believe in some cases very greatly in excess of the 75 000 V/cm which obtains in the present case. On the other hand, it is generally accepted that a given d.c. stress is equal in breakdown effect to a very much greater a.c. stress. As regards Mr. Highfield's comments on my transformer arrangements, he is quite correct in saying that I could carry out my system perfectly well with one three-phase/six-phase transformer and two three-core concentric cables. But I think he has overlooked the fact that this arrangement would not permit of 60 000 volts being exceeded without also exceeding the maximum potential gradient of 40 kV/cm, whereas the repetition of the arrangement, in the manner proposed in Fig. 11, permits of $\sqrt{3}$ times this voltage being employed, which of course gives a very great gain.

Mr. Dunsheath exhibited a lantern slide (Fig. B) showing a diagram of connections which he suggested would give the same results as my proposal. I am afraid he has not realized that his proposal would only transmit single-phase current and is therefore useless. He also exhibited a table purporting to give annual losses, in which, by assuming that the dielectric losses in my system went on undiminished for the whole 24 hours, he obtained a figure of 8 000 000 units per annum. If Mr. Dunsheath will refer again to the paper, he will see that my proposed method of regulation involves the entire shutting down of 4 of the 6 cables at times of light load. The effect of this is that his figure of 8 000 000 units for the losses of my system becomes 3 200 000, or less than in his own scheme. If, again, his number of cables were increased to 8 (at 50 000 V) the dielectric losses (even at full load) *would be greater* than in my system. On the other hand, if he were transmitting 100 000 kW the losses (both copper and dielectric) would be greatly in favour of the six-phase/three-phase system, and still more so (in the case of the copper losses) if the load factor were better than 40 per cent. The reason why he is able to use 66 000 V is solely because he works his insulation up to 50 000 V per cm. With regard to Mr. Dunsheath's statement that the author implies that the carrying of load currents in the intersheaths is one of the advantages of the system but that this same advantage can be claimed for any intersheath system, I submit most positively that this is not the case. It is true that the plain tapping system for intersheaths is as effective as my own for all intersheaths nearer to the central core than a point which is at half-way potential, but for intersheaths outside this point—and this is just the part where they are most needed—the essential difference between the straight-tap method and my own is that the latter uniformly preserves its load-carrying value with undiminished voltage of transmission, whereas the other method rapidly falls off in efficiency. There is therefore no inducement to use more than one intersheath. This is the reason why, in the intersheath arrangement which Mr. Dunsheath's firm has patented, only one intersheath can be efficiently employed. It requires only a very small calculation to see that the more intersheaths we could employ the more effective would the scheme be; also, I would particularly point out that in my own scheme the final intersheath can be brought very close to the outside lead envelope, and that this intersheath performs a very valuable function, in acting as a pilot wire, to cut out the cable temporarily before the damage has penetrated into the same, and may be used as an emergency connection to prevent a complete shut-down where the cable is not burnt through sufficiently to disqualify it totally. Under these conditions the said arrangement is equivalent to no less than 6 spare cables, on the assumption that the trouble always enters the cable from the outside. The outermost lead sheath has also another very important function in that it eases the situation at the junction boxes, and the nearer it is to earth potential the less risk there is of a breakdown at the junction box due to water getting into the latter. No doubt there is some truth in Mr. Dunsheath's statement that intersheaths may be valuable in redistributing the heat—particularly in triple-core cables—but I must totally disagree with his statement that "if an intersheath cable were left without the ends connected to transformer tappings the results would be quite as good as if they were connected." On the other hand, I can quite believe that, Mr. Dunsheath being limited —from the point of view of efficiency—to the employment of only one intersheath, and—from the point of view of space—to even less than one intersheath (owing to his determination to put three cores in a given cable), he rather naturally came to the conclusion that intersheaths were useless. With regard to Mr. Dunsheath's "S.L." type of cable (see Fig. C) and the table of losses which he gives in connection therewith, I may say that after this table has been corrected in the manner I have already indicated the only conclusion I can draw from it is that the loss in the lead sheath with this type of cable is, as I should expect, considerably more than in an ordinary type of cable.

The remarks of Professor Fleming in reference to compressed air are most interesting, but I cannot say anything upon this subject, not having made any study of the same.

North-Eastern Centre, at Newcastle, 11 December, 1922.

Mr. H. W. Clothier: The paper has two general objects, with which we should all be in perfect sympathy: (1) The covering with metal of long transmission cables in preference to the use of overhead lines; and (2) the reduction in the initial costs of insulating these conductors by suitable grading of dielectric stresses (potential gradient). In these general principles switchgear manufacturers have met with some success, and their influence has extended to the transformer terminals and the generator terminals. In fact, metal covering is now a possibility for all connections between the generator and the load, with the

notable exception of the long-distance transmission line in cross-country journeys where, in some cases, the increased cost of ordinary cables makes it too expensive as compared with overhead bare lines. These general principles have many advantages, e.g. safety to life, absence of interference by weather, elimination of the vexed problem of protection against lightning, and simplicity of maintenance. In fact, I was informed by an eminent engineer engaged upon transmission schemes across long distances in India, that, on account of the cost of patrol and repair, it was cheaper in the end to use high-tension cables than overhead lines. We have also the instance of the G.P.O., who are now engaged upon putting under ground a great many of their long-distance telephone lines. I think that the author should give us the cost of the overhead lines at 30 000 volts and 100 000 volts, to enable a comparison to be made with the cable schemes. I understand that by his method of connection there is some reasonable prospect of laying cables at a cost which would be little or no more than that of ordinary overhead lines. That being so, all that remains is to prove the economy and efficiency in operating the system. When one comes to examine it in detail, at first sight it seems so complex as to be likely to fail to receive that amount of welcome which its objects deserve. I have had the switches under Scheme B set out in diagrammatic form, and I had some difficulty in placing all the switches and transformers on the schedule. Under the major star transformers two sets of eight are given. I presume one set is an alternative to the other, but I can only find room for three at each end, so I presume that one at each end is spare. Comparing the systems, there must either be a considerable amount of energy lost in System B, or else it is designed for a more liberal load. System A has, at each end, 15 × 4 200 kVA = 63 000 kVA, whereas System B has (3 × 7 000 kVA) + (9 × 5 000 kVA) + (3 × 2 500 kVA), or a total of 73 500 kVA. Some adjustment of the connections would probably be necessary when the requirements for automatic protection against faults on the cables are investigated. Some scheduled as "isolating switches" would need to be automatic circuit breakers. Possibly the principles of self-balance protection could be applied to a pair of cables and the hexagon transformers but much complication would arise if we were to attempt to cut out one of a pair. I suggest also that the switching operations would require very careful handling. To close up on a line there would appear to be about 18 distinct switching operations to perform.

Mr. R. J. H. Beaty: The author has put forward a very ingenious scheme but there is one point with which I am not in agreement. The top of the hexagon is connected to the end of one phase of the "major transformer," presumably through a balance coil although it does not appear to be mentioned in the paper. The voltages supplied to the various cores of the cable are consequent voltages, the bottom of the hexagon giving a resultant, not a real earth. A dead short-circuit on one of the hexagon transformers might cause a potential difference of 60 000 volts between the outer conductor of the cable and earth. I see no reason why each hexagon should not consist of one three-phase transformer. The information given as to the behaviour of the dielectric is extremely interesting, and I feel that it could usefully be amplified.

Mr. G. V. Twiss: As one interested in overhead transmission, nothing would please me more than to find available, underground cables suitable for work at as high voltages as are possible with an overhead transmission line. Such high-voltage cables would be very helpful adjuncts to overhead transmission; not only for the bringing of transmissions into towns, but particularly in this country where one has to negotiate so many obstacles, such as road crossings, trunk P.O. lines, important railways and the like. The arguments in the paper are, however, in the main based upon the use of 33 000-volt cable to transmit 50 000 kW a distance of 30 miles. For such cases, however, this voltage is not an economic one, as the conductor requires a pressure certainly not less than 100 000 volts. To transmit this pressure a distance of 30 miles by means of overhead transmission, allowing, as an additional safeguard, two independent transmission lines, each carrying a single circuit, would cost not more than £150 000. Thus, based upon the author's data, we get the following comparison :—

	£
Using 33 000-volt underground cable ..	1 000 000
Using the author's system of underground cable at 100 000 volts	500 000
Using overhead transmission at 100 000 volts	150 000

Thus, whilst the author claims a big saving on ordinary underground cables, yet it would only be justified where the overhead system could not be used. It is difficult, however, to conceive a case of a 30-mile line that is not in the main over open country, for which an overhead line is more suitable than underground cable, so that the case given by the author does not appear to be one of economic practicability. I therefore considered the application of the author's system to what seems to me to be the practical case, namely, that of leading-in off an overhead transmission line into a town by underground cable. Apparently, however, the proposed system would involve transformation, necessitating an expenditure at least equal to that of ordinary stepping-down, or, alternatively, the overhead line would have to be built on the author's system, the added cost of which would offset any saving due to avoiding stepping-down. I am unable, therefore, to see the application of the proposed system to practical cases of transmission of the nature which he himself cites. Nevertheless, he has clearly put a great amount of work and trouble into working out this system, and has drawn particular attention to what is achievable from the application of the study of dielectrics and gradients, and there is much in the paper and the new ideas behind it which will open up new avenues of thought and will doubtless be very helpful to the electrical industry.

Mr. A. M. Taylor (*in reply*): Replying to Mr. Clothier, I regret that at the moment I have not any definite figures of the cost of overhead lines, but I may say that some time ago I examined the detailed costs of a very important American overhead line, and

my recollection is that these were approximately £0·1 per kW per mile. There was, I believe, a double line of towers, as well as circuits, and the cost of wayleaves for the towers was included. In the scheme proposed in my paper the cost of the cables, alone, approximates to £0·26 per kW per mile. At a very trifling extra cost, however, 100 000 kW could be transmitted over this line, and the cost in this case would be only of the order of £0·14 per kW per mile; and if it were possible to work at 150 000 volts and transmit 150 000 kW (as now seems more possible than when the paper was read) the cost would be reduced to about £0·1 per mile.

I greatly regret that I cannot fully answer Mr. Clothier's question about the transformers without extending this reply unduly. I may state here that his remark is substantially correct as regards the "B" system, except that it has (6 × 7 000 kVA) + (9 × 5 000 kVA) + (3 × 2 500 kVA), or a total of 94 500 kVA. The reason for this very large kVA rating is that the transformers are required to work at rather a low leading power factor, on account of the large condenser current, but, as pointed out in the estimate, if it should be found practicable to control the power factor in the way indicated in the paper, the requisite capacity of the transformers would be greatly reduced. The switching operations will, of course, be considerably simplified by adopting the arrangement of transformers which I have put forward in my reply to the London discussion (page 247). Possibly this diagram may sufficiently meet his difficulties.

In reply to Mr. Beaty, the top of the hexagon shown in Fig. 11 is connected to the end of one phase of the "major star" transformer through a balance coil, in the way that he presumes. This, however, is not the arrangement that I would naturally choose, but it appeared sufficient for the purposes of explanation. As a matter of fact, I had with me in London and Newcastle a lantern slide giving the arrangements which I should prefer, but there was no time to exhibit it. I do not consider that there is any serious point in Mr. Beaty's statement that "a dead short-circuit on one of the hexagon transformers might cause a potential difference of 60 000 volts between the outer conductor of the cable and earth." It is quite easy to prevent this. In any case the result would only be momentary and the cable should not be damaged by it. I do not consider that anything more need be provided for in my scheme than an insulation between any outer core and earth equal to withstanding 30 000 to 40 000 volts, if necessary, during emergency conditions.

In reply to Mr. Twiss, my proposal was not really intended to be employed for running across country, but has so far been designed exclusively for employment on railways. It remains to be ascertained whether the cost of running overhead lines across country will not be expensive if a duplicate line of towers be installed, and I maintain that nothing less than this should be done. Wayleaves have to be obtained, not only for the sites for the towers but also for continued access to these towers with repairing gear; and when the big towns are approached, or even in the more densely populated parts of the country between small towns, as in Lancashire, Yorkshire, Kent and Surrey, etc., it may prove very difficult to get wayleaves without considerable expense. Then there is a difficulty which I have already mentioned elsewhere, viz. the question of aviators flying into the overhead line in fogs or at night time, with possibly very disastrous results. Also, the question of malicious interference has to be considered. I have already mentioned in my reply to Mr. Clothier that the cost of my system if applied to transmit 150 000 kW at 150 000 volts would come down to the order of £0·1 per kW per mile. This would give interest and sinking fund charges, on a 30-mile line, of the order of 0·022d. per unit (total for whole line). I believe that a combination of the overhead system with my system for the entry into towns might not be impracticable, when we bear in mind that at least six of the conductors have to be insulated for only 15 000 volts to earth and another six for only 30 000/40 000 volts to earth. I agree with Mr. Twiss that my system should only be used where it is inadvisable or inexpedient to install the overhead system. If, however, wayleaves can be obtained along the railways and if the system become common both to the railways and to municipalities along the line, a very different aspect will be put upon the case.

South Midland Centre, at Birmingham, 13 December, 1922.

Mr. G. Rogers: The advantages claimed for the new method of long-distance three-phase power transmission put forward by the author are of such an order that the scheme calls for the most careful attention of engineers interested in the matter. If the saving in capital cost of the new scheme as compared with the normal three-phase transmission at 30 000 volts by means of three-core cables is only half that claimed by the author, then it seems to me that a strong case has been made out. To turn to the practical consideration of the scheme the connecting up of the transformers and switchgear both at the sending and receiving ends would appear to be rather complex and difficult. I should like to ask the author how he proposes to dispose of the inner lead sheath at the terminal ends of his cable. Also, the question of the electric protection of the cable has not been mentioned, and perhaps the author will say whether he has considered this important matter. It would appear that the usual methods of protection would not apply, and special arrangements would have to be devised.

Mr. F. Forrest: The estimates of possible saving to be effected by the adoption of the author's system as against the use of ordinary three-core, 30 000-volt cables are so great that one wonders whether the estimates are based upon really reliable manufacturing costs. As far as I am aware there is no cable of the type proposed by the author as yet actually made, and,

until the system has been tried, many people will regard these estimates of cost with a good deal of scepticism. The superiority of 25 periods over 50 periods for long-distance transmission has not been dealt with by the author and it would be interesting if, in his reply, he could indicate what the reduction in the losses would amount to if the lower frequency were used. When very high potentials and long-distance transmission lines are considered, especially when underground cables are used, the superiority of a low frequency becomes very marked, and from the point of view of dielectric and sheath losses it should be possible to produce a cheaper and more reliable cable with 25-period working than with 50-period working.

Mr. R. H. Rawll: I should like to draw attention to the formula $i_d = 2\pi fce/\sin\theta_d$, which appears on page 222. The author gives e as the "voltage between core and intersheath." As a concentric ring of insulation is being considered, of which the capacity c per foot length has already been calculated in a previous formula, and since i_d is the capacity current flowing radially through this ring, e must be the potential difference across this ring and not as stated above. An example will make this clear. If the tenth layer of insulation is taken, for the sake of argument, the voltage absorbed by this layer is (from Table 1, Appendix C) 1 840, which is obviously the value of e to be used in the formula in question. If, however, e is as defined above, this value would be 41 250 volts, i.e. the voltage between the core and this layer—a very different thing indeed. That the author does not mean this latter figure to be taken is very obvious from a perusal of the calculations given, and I merely point out this apparent discrepancy in case others, on substituting the various quantities into the equation, should find a difference between their own calculated results and those tabulated.

Mr. W. J. Line: In the right-hand portion of Fig. 8 the author proposes to superimpose on the two six-phase systems which are linked together, and represented by the two hexagons, a 123 000-volt single-phase supply. In Fig. 10 *et seq.* it is similarly proposed to superimpose a three-phase supply at increased voltage (represented by the "major star" in the figure) on the three inter-linked six-phase systems represented by the three hexagons, and thereby transmit increased power. How does this affect the current-carrying capacity of the cables in the separate hexagons? It appears to me that the proposal must involve more current in the lines. Does not this mean that their size must be increased? On page 230 the author points out that at light loads the charging current in the line, due to its capacity, would be reduced to about one-third of its maximum. He proposes also to offset the charging or leading current by the magnetizing or lagging current of an induction motor or transformer load, and thus reduce or eliminate the wattless current to be supplied by the station. Now at times of light load, unless the reduction took place through the actual shutting-down of motors, the lagging or magnetizing current of the motor load would not fall off in the same way as the leading or charging current of the line. An induction motor takes the same magnetizing current whether running light or fully loaded. Therefore it appears to me that the lagging and leading currents could not always be balanced against one another under varying load conditions, and at times resonance conditions might arise. However, the proposal has the advantage that under all the circumstances the generating station would be relieved of the supply of some at least, if not all, of the wattless current.

Mr. W. Lawson: The author's scheme, owing to the exhaustive treatment of the details, appears at first to be unusually complicated, but this impression largely disappears with a fuller grasp of the scheme as a whole. In separating the phases, and in the particular method of employing intersheaths for the better distribution of dielectric stresses in the insulation, the author has succeeded in designing his cables without introducing any condition of working which is not already met with in E.H.T. transmission cables. The really novel and debatable feature of the scheme is the author's arrangement of the transformers. Here some complication creeps in with the necessity of having to employ a large number of transformers of various primary and secondary voltages, but providing there is no serious disadvantage in this (and such is not self-evident) the objection to the scheme on the score of complexity is discounted. Since the discussion the author has informed me that he proposes to discard the superposing transformers, while still transmitting power at 100 000 volts through the central cores. With this modification the scheme will take the form of a triple six-phase transformer scheme. The author mentions the difficulty of jointing single-core cables having a hempen centre. Does he consider this to be more serious than the jointing of his own cables? A valuable feature of the scheme consists in the possibility of taking up loads of poor power factor, with a gain in efficiency and regulation. I consider, however, that the figure of 0·7 which the author has assumed as the probable average power factor of the substations' loads is too low, in view of the attention which is now being given to the improvement of consumers' power factors. In the comparative costs of 30 000-volt and 100 000-volt schemes detailed in Appendix E, the costs of trunk cables for the former include laying, and excavating and reinstating streets, but apparently the cost of this work has not been included in the amount given for cables in respect of the 100 000-volt scheme. I shall be glad if the author will explain this point.

Mr. A. M. Taylor (*in reply*): Mr. Rogers raises the question of the electric protection of the cable. This has had some consideration, and I have discussed the matter with Mr. H. W. Clothier, and also indicated in the discussion before the North-Eastern Centre (page 250) a method of protection which I believe would be quite efficacious without the use of pilot wires. The problem is not nearly so complicated as it appears at first sight, but one must first get a thoroughly clear idea as to what the different currents are doing in the two systems.

In reply to Mr. Forrest, the estimates for the cables were given to me by thoroughly reliable firms, and since—in most cases—the same firms gave me estimates for ordinary three-core cables, they would not be likely to magnify the expense of the latter in their estimates.

In reply to his question as regards the superiority of 25 periods over 50 periods, it may be said that the doubling of the frequency doubles the hysteresis loss in the dielectric, and also doubles the capacity current; it quadruples the dielectric loss due to capacity current; it quadruples the regulation of the line due to the "capacity rise"; and it also quadruples the lead-sheath loss. It is therefore evident that a 25-period cable is inherently much less likely to break down than a 50-period cable, and, if this were the only question to be considered, one would say at once that it is most unfortunate for long-distance transmission by underground cables that 50 periods has been decided upon as the standard periodicity. It is therefore evident that considerably greater distances can be covered with 25 periods than with 50 periods, also that armoured cables can be safely used, with negligible loss in lead sheath and armouring.

Mr. Line is correct in surmising that additional copper is required for the superposed current. It is stated in the paper that additional copper to deal with this current is placed in the central core at a quite reasonable extra cost on the cable. Mr. Line's statement that an induction-motor load takes the same magnetizing current, whether running light or fully loaded, is correct. What he has not pointed out, however, is that as the load on the induction motor is reduced, the reduced load becomes the equivalent of a greatly increased dead resistance, and this dead resistance is of itself quite sufficient to check any resonance. There is also the other point of view, i.e. that motors are switched completely off and on, and, as they are all in parallel with one another, the magnetizing component of the motors left in circuit is equivalent to a large reduction in the total magnetizing component of all the motors on the system; from both points of view, therefore, the movement is in the right direction.

I thoroughly concur with Mr. Lawson's remarks, and I am pleased to note that he agrees that the scheme becomes a simple one when the superposed major star is removed. On the question of power factor I should like to ask Mr. Lawson to bear in mind that Birmingham is particularly favoured in the matter of power factor owing to its large rotary-converter and tramway load, but that even in Birmingham the pure motor-load power factor is sufficiently low to fulfil my suggested conditions. In reply to his last remark, I do not debit my scheme with the cost of excavation and of remaking the streets, because it presupposes the running of the cables along the main lines of railway by the permission of, and for the benefit of, the railway companies.

ELECTRIC ARC WELDING APPARATUS AND EQUIPMENT.

By J. CALDWELL, Member.

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SUMMARY.

The intention of this paper is to deal with the physical features of the iron arc as used for welding ferrous metals, so far as those features are known, indicating some of the lacunæ in present knowledge; and to describe the general types of apparatus and equipment which have been developed, illustrated by some examples of each type, and some of recent design which promise well.

The two branches of the subject are directly connected, because the apparatus must conform in its performance to the conditions of the welding arc and to the requirements of the welder.

Operating or workshop methods are touched on only so far as they illustrate or determine, or are determined by, the physics of the welding arc and the practical requirements of welding.

Working methods and applications of arc welding have been described in several recent contributions to other Institutions and Associations, in technical journals, and in books, reports, etc. A short list of the more important of these within the author's knowledge is set out in Appendix II at the end of the paper.

CONTENTS.

(1) THE STATE OF THE ART.

Arc-welding practice is in advance of theory. It is an established fact that good welds can be made on any ferrous material if certain conditions are observed, and the standardization of these conditions has been established for many applications by empirical methods. As usually happens in an empirical art, there is considerable divergence of opinion on many points which can only be reconciled by the establishment of exact knowledge.

Arc welding was originally tried for repair work, either because there was no other method or because it was evidently quicker and cheaper than any other. It was looked on with suspicion, but when time was of importance and new parts were not readily obtained, the successful use was worth risking and failure did not harm the existing position. During the war the conditions favouring such trials were intensified, and the generally good results obtained greatly widened the applications, developed welding as a regular repair process and led to its adoption for constructional work.

Ship repairers led the way in this empirical development, assisted by their wide knowledge of ferrous materials and methods of joining them up into structures exposed to severe, complex stresses. They have had the co-operation of electrical engineers, metallurgists and chemists, who have investigated the subject, each from his own point of view. There has been a certain amount of systematic research work, directed, however, rather more to immediate practical results than to fundamentals.

A greater knowledge of the physical foundations of the process is desirable as a guide for practical development, and as a basis for confidence. If it can be demonstrated that this method of uniting steel and iron parts gives consistently good results, not inferior to the older methods, the saving in weight and labour will lead to its adoption as standard practice in lieu of the older methods of riveting, screwing and bolting.

A great deal of work has been done to ascertain the electrical conditions necessary for good work, their more or less automatic control by suitable apparatus, the adaptation of electrode material and fluxes to the particular metals to be welded, and the training of operators.

The object of this paper is to endeavour to put the results of this work on record, within the limits indicated above. The paper does not deal with carbon-arc welding, which is well established for certain manufacturing work, except to mention some physical facts which have a bearing on the iron-welding arc.

(2) IRON-ARC CHARACTERISTICS.

The physics of the carbon arc as applied to lighting have been investigated by Mrs. Ayrton in her well-known work. Making allowance for the difference in the behaviour of the electrode materials and the purposes to which it is applied, it is assumed that the facts established are generally true for metallic arcs, and the iron arc in particular.

The distinctive characteristic of an arc is that the current is carried by a gaseous or quasi-gaseous conductor composed of gas, vapour, very fine solid particles, or a mixture of such bodies, across a gap between terminals or electrodes which by volatilization or disintegration furnish a supply of the quasi-gaseous conductor. It is therefore essential that one or both

of the electrodes shall be maintained at a temperature producing such volatilization or disintegration. The gaseous conductor behaves as one having a negative temperature coefficient: high temperature is a condition of its conductivity. The volatilization temperature is produced by the passage of the current across a relatively high surface resistance or contact resistance located at the junction of the gaseous conductor and the electrode. The electrode in the carbon arc is solid, while in the iron (and other metallic) arc it is liquid, i.e. molten. This contact resistance appears to be related to the volatilization temperature and heat of the electrode material, and to require a minimum current density for any particular electrode material. This results in a fixed voltage-drop at the contact surface where volatilization occurs. The voltage-drop along the gaseous conductor is proportional to its length, so that it appears to have a definite specific resistance. If volatilization takes place at one electrode only, as in the direct-current carbon arc, the surface resistance and voltage-drop are lower at the other electrode. In the carbon arc the temperature at the volatilization surface is higher than at the other, i.e. the positive electrode is hotter than the negative. The volatilization surface is the seat of the highest temperature in the arc.

The total voltage-drop between the electrodes is therefore the sum of three terms: two at the contact surfaces between the electrodes and the gaseous conductor, and one in that conductor. The surface voltage-drops are fixed for any particular electrode material, while that of the gaseous conductor is proportional to its length. For variations in current, the electrode material and arc length being fixed, the contact-surface areas and the cross-section of the gaseous conductor automatically vary so as to keep the current density in each constant. The resistance of the whole arc therefore varies inversely with the current passing, and the arc is unstable in itself. These statements are subject to qualifications, but are at least first approximations. The conditions of the carbon arc change suddenly at a current density which brings the positive contact surface (crater) to the edge of the electrode, producing the unstable "hissing" arc.

The numerical values of the voltage-drops and some other elements have been investigated by Mrs. Ayrton for the carbon arc in air. For arcs between metallic electrodes they are not definitely known. There is evidence that, between iron electrodes of equal size, the positive electrode gas-surface develops more heat than the negative. Presumably, therefore, it is similar to the carbon arc in having a higher voltage-drop at the positive electrode. It is known that the total voltage-drop across an iron arc is considerably less than that across a carbon arc, and it is probable that this lower voltage corresponds to a smaller amount of energy consumed in the volatilization of iron compared with that required to volatilize carbon. The energy of volatilization is not a question of temperature only, different metals, as they have different "latent heats of fusion," doubtless having different "latent heats of volatilization." In the special case of carbon, volatilization takes place from the solid state, the liquid state being non-existent at ordinary pressures, so that the latent heat of a double change of state is involved. From calorimeter determinations on fuels, the heat of vaporization of carbon from the solid amorphous state is 3·231 calories per gramme, or 5 817 B.Th.U. per pound. The temperature of volatilization is about 3 600° C. The author is not aware of similar data for iron or other metals of high melting point.

In the carbon arc the volatilization temperature is reached at the positive electrode only, with a drop of about 30 volts. According to Mrs. Ayrton, the volatilized carbon is projected from the positive to the negative electrode as a "carbon mist." In air some of this carbon mist is burnt, with the production of a sheath of flame around the arc proper. Some of it—in arcs of normal length—reaches the negative electrode, on which it is deposited.

It has been rather generally assumed that a similar projection of metal takes place across an iron arc, from positive to negative, but this is not in accordance with welding practice. Deposition takes place equally well whether the electrode or the work is positive, and at least as well with alternating current as with direct current. It may be suggested that the cause of the transfer of iron is different from that in the case of carbon, but there is at present no ground for supposing that there are different processes to bring about similar results. Both cases are covered by the single statement that electrode material is transferred from the hotter to the cooler electrode. The question as to whether the transferred metal travels in the state of vapour, a fine spray, or otherwise, has been much discussed, and there are various opinions. One American investigator claims to have proved that it is in the form of drops numbering 30 000 to the ounce, which may be called a spray. That there is a definite projection is certain, for in overhead and vertical welding the iron passes against gravity from the electrode to the work. Although there is evidence that more heat is evolved at the positive electrode than at the negative, the greater mass and conductivity of the work keep the temperature below that of the electrode, even with the work positive.

The minimum pressure needed to maintain an iron arc is known to be about 15 volts. This covers the sum of the two surface resistances and that of the gaseous column. The separate values of the three terms are not known. As the welding arc is very short, it can be said that the sum of the two surface voltage-drops is something under 15 volts. This is not very different from one-third of the similar drop in a carbon arc. In a carbon-iron welding arc with a ½ inch diameter carbon negative, an arc length of ¼ inch and a current of 200 amperes flowing, the total arc voltage is 22. If the voltage-drop at the carbon is the same as at the negative of a carbon-carbon arc, i.e. about 9 volts, these figures indicate that the principal difference between the carbon and iron arcs is in respect to the voltage-drop at the positive electrode. Probably the conditions of a welding arc are analogous to those of a "hissing" carbon arc, in which the voltage-drop at the positive is less than in a steady arc.

From these statements it appears that there are

two very definite openings for research on the welding arc, viz. (1) In what state does the iron cross the arc, and what conditions determine its transit? and (2) What is the distribution of voltage-drop in the

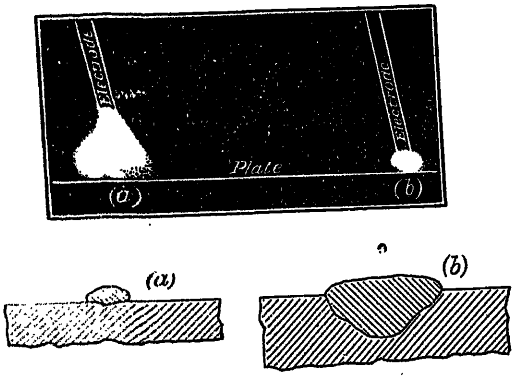


FIG. 1.—Long and short arcs.

iron arc? Another is: What are the quantitative relations of this transfer of metal to the electrical and other variables?

The practical object of research on the subject must be to determine the conditions which make the useful transfer of electrode material a maximum. "Useful transfer" covers a rather wide ground.

Like the carbon arc, the iron arc behaves as if it had a negative resistance, i.e. an increase of current across an arc of fixed length reduces the voltage-drop. It is therefore inherently unstable, and, since good welding demands the maintenance of a steady current proportioned to the size and composition of the electrode and the character of the work, all welding equipments have to include some means of adjusting the current and keeping it within limits during the operation.

The figure of 15 volts for minimum welding-arc voltage-drop is derived from tests made with direct current, bare iron electrodes and automatic feed of the electrode. With hand operation the voltage is always higher, i.e. from 22 to 25 volts. This is for the mechanical reason that the hand cannot maintain steadily the very short arc, about $\frac{1}{16}$ inch, corresponding to the minimum voltage, but has to work with a minimum length of about $\frac{1}{8}$ inch. Flux-covered electrodes appear to permit of a somewhat greater working length and voltage, thus rendering the manipulation easier. It is rather difficult to measure the true arc length with flux-covered electrodes, as the metal "cups" a little above the edge of the covering.

If the arc is lengthened much beyond the figures given, good welding is impossible. The iron passing across the arc burns to oxide, absorbs nitrogen, and the deposit is contaminated, permeated with blow-holes, mechanically weak, and may fail to unite with the metal of the work. The arc length at which this defect commences is variously stated as that corresponding to from 27 to 30 volts. It is probably rather higher for covered electrodes and for alternating current.

The fact that good welding can be done only within a rather narrow range of arc length and voltage imposes another condition on welding equipments, i.e. they should not permit of an arc voltage exceeding the maximum for the deposit of good metal. If an arc is drawn beyond this it should be extinguished. Fig. 1 shows the appearance of long and short arcs, and their effect, and Figs. 2 to 6 illustrate degrees of penetration.

This condition has to be reconciled with the fact that the open-circuit voltage must be in considerable excess of the arc voltage to provide for the voltage-drop in the steadying resistance or reactance required to make the circuit reasonably stable, and also to permit the arc to be struck readily.

Facility of striking the arc is an important element in the time and labour costs of arc welding. Whilst a sufficient open-circuit voltage is necessary, if the circuit conditions permit the passage of a very large current at the moment of contact the electrode may stick or "freeze" to the work, making a sort of resistance weld, which is not wanted. As the longest electrode which can be conveniently used is consumed in a run of 1 to 3 minutes, such interruptions add materially

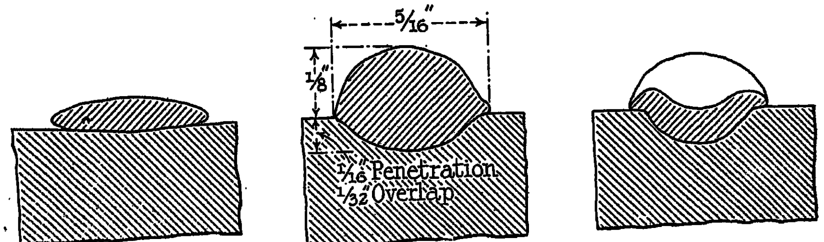


FIG. 2.—Small penetration. FIG. 3.—Good penetration. FIG. 4.—Good penetration of crater.

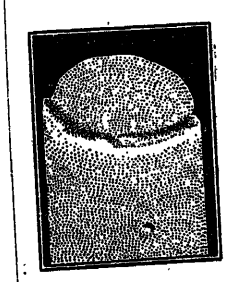


FIG. 5.—Good penetration (section).

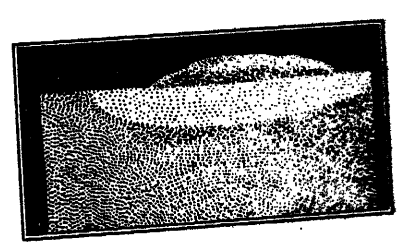


FIG. 6.—Poor penetration (section).

to the time spent in changing the electrodes. Fig. 7 shows photo-micrographs of welds.

Some experiments designed to throw light on certain of the questions raised in this section of the paper have been made by Mr. H. M. Sayers and Mr. Langdon Davies at Faraday House and elsewhere. These experiments and the deductions from them are described in Appendix III.

(3) Direct-current versus Alternating-current Welding.

Good welding can be done with both direct and alternating current. There are preferences, and as direct current had the start more operators and others were in favour of direct current than of alternating current. The best electrical conditions are slightly different, and there are differences in the actual manipulation, but experience shows that operators who have been accustomed to one readily adapt themselves to the other. It is also the case that flux-covered electrodes are essential for alternating current, apparently because the lagging effect of the flux and slag maintains the necessary temperature during the periodical current reversals. The only real difference is that the striking of the arc is rather more difficult with alternating current.

A higher open-circuit voltage is required with alternating current. With direct current an arc can be maintained with a minimum of 45 volts (open circuit), but 60 volts is much easier to work with and can be taken as the practical figure. A higher voltage permits of an excessive arc length and a poor quality of deposit.

With alternating current the open-circuit voltage should be from 75 to 90 volts. The difference between the arc voltage and the open-circuit voltage has, in the case of direct current, to be taken up in a steadying resistance, while a reactance is used with alternating current. There is therefore not so much difference in the steadying losses as might be supposed. It may, indeed, be possible to make alternating current more efficient in this respect than direct current, as will appear later in the descriptions of some of the equipments available. The alternating-current arc has a lagging power factor, but the magnitude of this depends a good deal upon the steadying and regulating equipment, and it need not be lower than that of the average works induction motor at full load.

Where it is desired to make use of a general public supply for welding, direct current imposes the necessity for the use of some form of motor-generator. The pressure of the public supply mains is generally 200 volts or more. To take from such mains welding currents of from 30 to 200 amperes per operator is not practicable or economical, for, in addition to the waste, the large bulk and high cost of the resistances, the open-circuit voltage is far too high. Further, public supplies generally have an earthed neutral, and the earthing of the work welded, which is often unavoidable and always advisable, cannot be permitted by the supply authorities, who also will not be pleased by the intermittent peak of hundreds of amperes. With an alternating-current supply the voltage reduction requires only a transformer.

(4) Electrodes.

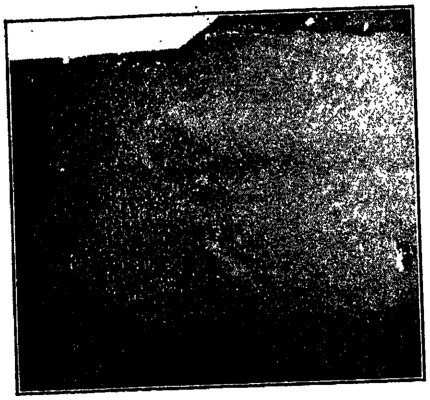
The first iron-arc welding was done with bare-wire electrodes. These are still widely used, and for some kinds of work where strength is not material the welds made may be satisfactory. With direct current operating on mild steel and wrought iron, flux-covered electrodes provide better results. For welding cast iron, high-carbon steels and alloy steels, and generally with alternating-current welding, flux-covered electrodes are necessary.

With bare electrodes there is oxidation of the electrode itself beyond the arc, and of the weld metal and work whilst they are hot. A suitable flux-covering protects the electrode beyond the arc, forms a protective slag on the deposited metal and work, and reduces the access of air to the arc itself. The arc length is somewhat greater and the current steadier, probably because the current is confined to the electrode end, and it cannot reach the outside. Manipulation is easier, as the arc can be struck on hot slag without any liability of the electrode to "freeze on." The deposit from a covered electrode on to a flat surface spreads more than that from a bare electrode, owing to the fluxing action of the slag, thus making a wider union and a neater finish.

Coated electrodes are essential for use with alternating current, probably because the coating and slag conserve the temperature during the periodic variations of the current.

The flux coating plays a very important part in welding high-carbon steels and alloy steels and cast iron, where it is necessary to obtain weld metal approximating in composition and structure to those materials. The electrode metal passing through the arc is considerably altered in composition; for example, carbon and manganese are burnt, or rather oxidized, by the reducing influence of the arc. The flux coating reduces the amount of this change, and may impart or restore the desired constituents. Whether this action takes place in the arc, or between the flux and the deposited metal, or partly in each, cannot be said. In the manufacture of steel the reactions between the metal and the flux in the furnace are essential parts of the process, and the composition of the flux is carefully adapted to the product desired. In arc welding, however, the time available for reaction is very short. This short time, the high temperature and the fine division of the electrode metal passing through the arc, are conditions widely different from those of the steel furnace, and a great deal of experiment has consequently been needed to arrive at the proper fluxes for different materials. In matching any particular steel the composition of the electrode and the flux co-operate. The electrode metal does not, as a rule, match that of the material. The work of producing electrode and flux combinations which will make good welds in different materials has met with great success. It has necessarily been done empirically, as no general principles can yet be formulated.

In the result, cast iron, manganese steel, nickel steel, stainless steel and other special alloy steels are all successfully arc-welded by the use of appropriate electrodes and fluxes.



A

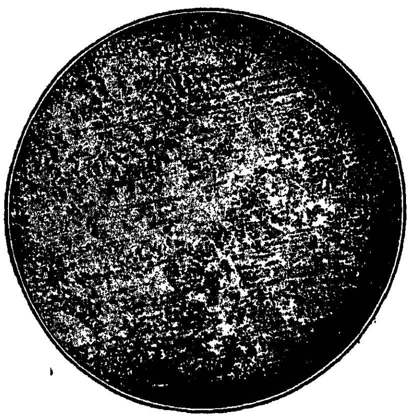
Magnification = 8 diameters.

B

Magnification = 8 diameters.

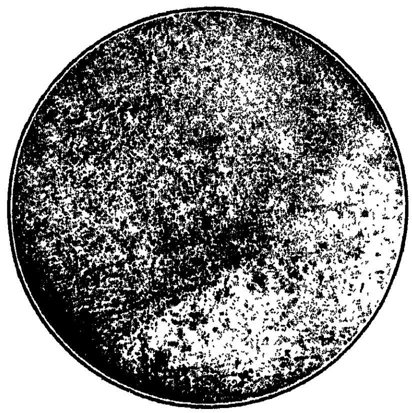
C

Magnification = 8 diameters.



D

Magnification = 40 diameters.

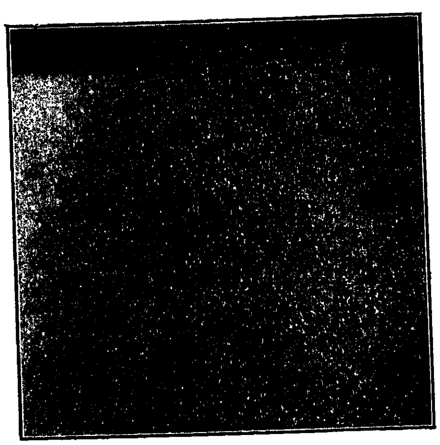


E

Magnification = 40 diameters.

F

Magnification = 120 diameters.



G

Magnification = 4·8 diameters.

H

Magnification = 120 diameters.

Magnification = 120 diameters.

FIG. 7.—Micrographs of arc welds: A to F are of mild steel; G, H, I are of cast iron.

(A) and (B), good welds. (C), poor weld; gas trapped on weld line and in weld metal. (D) and (E), weld or interfusion line. (F), weld line. (G), cast-iron weld. (H), weld line of (G). (I), weld metal of (G).

For most purposes a flux coating of a basic nature is desirable, but in some cases it is of an acid description. An aluminium wire or tape is sometimes included, and nickel plating is also used. Both these metallic additions tend, in different ways, to reduce oxidation of the electrode metal, and may also have other effects.

The metallurgical and chemical actions of the coating and the flux formed by it have to be reconciled with other requirements. The coating must fuse at a slightly higher temperature than the metal, while the slag formed must be very liquid and light so that it will rise to the surface before the metal solidifies and will spread over the hot weld and so protect it from the air. The flux should dissolve or reduce the iron and other oxides. The glassy skin of cooled slag should be easily removed from the welded surface by brushing or light hammer chipping, and the coating must be sufficiently tough and adherent to the electrode to withstand transport and handling. In working, the coating must fuse evenly without flaking and must keep level with the end of the electrode. There is usually a little "cupping," i.e. the electrode end is a trifle inside the fused rim of coating. Deep cupping is, however, objectionable, as a projecting rim of fused coating interferes with the arc striking and misleads the operator in respect to the length of arc. Whilst hot the slag is a semi-conductor and the arc may be struck on it without any risk of the electrode sticking.

Intermediate between bare and coated electrodes are dipped electrodes, i.e. electrodes dipped into a "slurry" of a basic nature. This coating has some protective influence on the electrode as against oxidation, and reduces spluttering and current fluctuations as compared with bare electrodes. It is not a substitute for flux coating.

(5) Current Density.

The current required for welding depends mainly upon the thickness and mass of the parts to be joined. It may be said roughly that the dimensions of the work determine the current, and the current determines the size of the electrode. For each gauge of electrode there is some maximum manageable current. If this maximum is exceeded the electrode fuses far beyond the arc, large portions drop, the current fluctuations are wild and the arc is turbulent and unmanageable. For coated electrodes the maximum currents range from 60 amperes for No. 14 gauge to 200 amperes for No. 4 gauge. The current densities thus vary from about 12 000 amperes per square inch for the smaller, down to about 5 000 amperes per square inch for the larger. Somewhat higher current densities can be used with bare electrodes. The American practice, which is chiefly with bare electrodes, is to use 10 000 to 12 000 amperes per square inch.

An electrode is capable of welding properly with two-thirds or less of the maximum current, so that six gauges, i.e. Nos. 4, 6, 8, 10, 12 and 14, cover a long range of work. A current of 200 amperes and a No. 4 electrode are about the manageable maxima for hand welding. Whether automatic welding will permit of larger values has not yet been determined. Automatic arc welding is hardly beyond the experimental stage in commercial service.

The statement made above (that the current is determined by the dimensions of the work) is subject to some qualifications. For example, in making a butt weld between two plates, say, $\frac{3}{4}$ inch thick, the edges will be bevelled, forming a V of an angle of about 60° when approximated. The first run of welding must be done with a small electrode, say No. 8, in order to get the electrode to the bottom of the V, which must be first filled. A second run is then made over the first with a larger electrode, and a third may be necessary. As the area or width increases, the electrode size and current required increase.

Mr. H. M. Hobart, who has taken a leading part in electric arc-welding development and research in the United States, says that the largest current which can be used makes the soundest welds. Too large a current for the thickness and mass of the work burns holes in it.

Welding thin sheet is practicable but has not been much developed, possibly because oxy-acetylene and resistance welding have a firm hold on this class of work. Recent experiments, however, promise good results, and thin sheet arc welding may prove commercially valuable.

(6) Polarity.

It is the established practice to make the work positive and the electrode negative. This practice seems to have originated with carbon-arc welding, the reason being that, with a positive carbon electrode, carbon is carried across the arc into the work, and the weld is unmanageably hard. With iron electrodes the reason for making the work positive is that, as more heat is evolved at the positive electrode, the greater conductivity of the work is countered and the work surface raised to the fusing point with a smaller current than would otherwise be necessary. The total heating of the work, and expansion and other troubles due to such heating are reduced. It is exactly analogous to the well-known fact that to solder fine work with the smallest heat-damage, the soldering bit should be as hot as possible.

(7) Direct-current Single Welders.

Output.—For general-purpose sets, the maximum loading is 200 amperes at 60 volts. This current is about as large as can be managed in hand operation.

Regulation.—This is the special problem of the single-welder set. The ideal characteristic for such a machine is a flat voltage characteristic from zero up to the full current for which it is adjusted, and a very rapid voltage-drop with any greater current. A general-purpose machine must have some means for varying the current at which this voltage-drop occurs. To prevent sticking, it is necessary to limit the current on striking the arc. It is desirable that current fluctuations caused by the unavoidable variations in arc length shall be checked and limited. The requirements may be summarized as follows:—

(1) A drooping characteristic for any current beyond that fixed by adjustment.

(2) A uniform voltage for currents up to the set or adjusted load, with little or no increase at no load.
(3) Very rapid regulation to counter the effect of arc variations.

The devices employed with more or less success to meet these requirements can be roughly classified as follows :—

(1) Excitation methods. Combinations of self excitation, separate excitation, direct and reversed series excitation. Special arrangements of the magnetic circuit, including pole disposition, proportions and shapes of poles, pole-pieces and yokes, calculated to vary the armature reaction with different load conditions. External regulators acting on the exciting circuits.
(2) Regulation of speed or torque of driving engine or motor by electrical control of governor or transmission clutch.
(3) External regulators controlling resistances in the welding circuit, sometimes acting simultaneously on one or more of the exciting circuits.

With those automatic regulations it is always necessary to adjust the field rheostats to suit the current

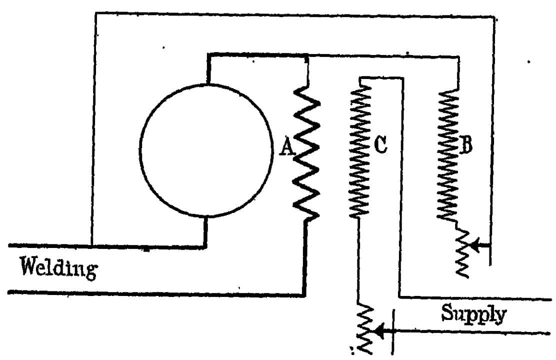


FIG. 8.—Connections of Premier welding set.

needed for the particular work in hand. The ideal set requires only this one adjustment, the automatic devices keeping the output at that level.

Most of the single-welder sets on the market employ one or more of the devices classified above, and some of them are very complex. Such devices as separate exciters and multiple field windings cause a generating set to be larger and much more expensive than a plain generator of the same maximum output.

A sufficient rapidity of regulation to counter arc irregularities is rather difficult to secure. Magnetic flux-changes in fairly massive iron circuits involve time-lag, and inductive action between different windings on the same magnetic circuit has to be allowed for. It is doubtful if the generator can be so altered as to control arc fluctuations. An American designer has recently found it necessary to explain his proposals for a thoroughly automatic single welder by several pages of equations culminating in determinants which reduce into cubic equations and have a forbidding appearance.

Single-welder sets are generally arranged for mounting as self-contained portable machines, with internal combustion engines of the motor-car type, or with driving motor, on trucks or otherwise to suit the users.

The examples selected for illustration are in use, and are typical of the many different machines proposed to give characteristics meeting the requirements of arc welding by automatic variation of excitation.

(i) *Kramer type*, adopted for the Premier set. The connections are shown in Fig. 8.

A = reversed series winding in welding circuit.
B = shunt winding, self-excited.
C = shunt winding, separately excited.

B and C are wound in the same sense, and A in the opposite sense. In series with B and C there are rheostats for the regulation of the welding current.

(ii) *Macfarlane type*, adopted for A.W.P. set. The connections are as in Fig. 9.

Four-pole field.

A = shunt winding on one pair of diametrically opposite poles, separately excited.
B = shunt winding on other pair of diametrically opposite poles, self-excited.

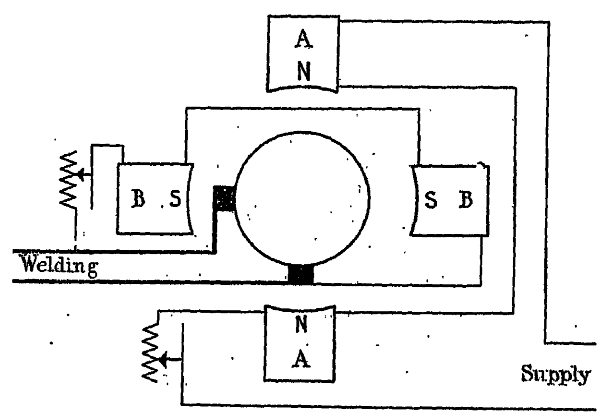


FIG 9.—Connections of Macfarlane (A.W.P.) welder.

A and B are wound in the same sense, and each has a rheostat in series for the regulation of welding current.

The pole-piece form, etc., are designed to facilitate armature reaction, giving a result similar to that of a reversed series winding.

The characteristics of this machine with the regulator in three different positions are shown in Fig. 10.

(iii) *Westinghouse, American*. The connections are as in Fig. 11.

A = shunt field, separately excited.
B = reversed series winding.
C = commutating winding.
D = shunt winding, differential. This winding is self-exciting while the generator voltage exceeds the separate supply voltage, as reduced by the rheostats; and is reversed and assists the series winding to limit the generator voltage when striking the arc.

A characteristic of this machine is shown in Fig. 12.

(iv) *Split-pole type* (*General Electric Co., American*). The connections are as shown in Fig. 13.

A = shunt winding, self-excited, on main poles, viz. those on the horizontal diameter.
B = shunt winding, self-excited, on cross poles, viz. those on the vertical diameter.
C = series winding in welding circuit, on cross poles, reversed with respect to the shunt winding.

The main poles are normally saturated; the cross poles are not saturated but provide a path for the

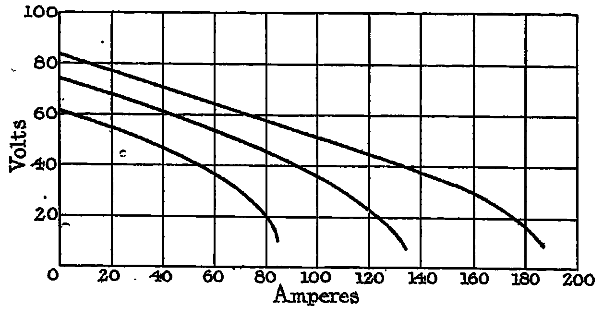


FIG. 10.—Characteristics of Macfarlane (A.W.P.) welder.

armature reaction flux, which is assisted by the series winding. The series turns are adjustable for different welding currents. At a given load the cross field is reversed by the sum of the armature reaction and the series winding effects. On short-circuit the reverse field cancels the main field, giving zero voltage. At any load the voltage is proportional to the arithmetical sum of the main and cross fields.

(v) *Simple shunt-series combination* (*Mawdsley and others*). The connections are shown in Fig. 14.

A = shunt winding, separately excited.
B = series winding in welding circuit, reversed.

Some of the machines of this type have pole-pieces, etc., designed to facilitate armature reaction.

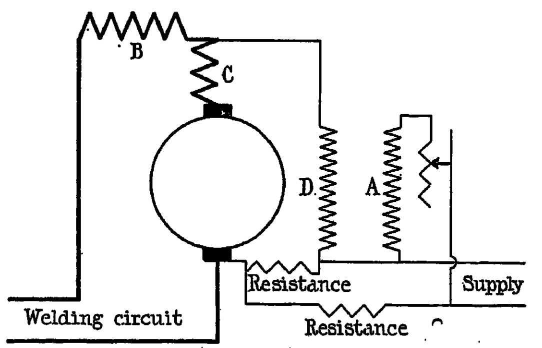


FIG. 11.—Connections of Westinghouse (American) welder.

With the two field windings so disposed to have considerable mutual induction, there is a large rise of current during a few hundredths of a second on a short-circuit, as shown in Fig. 15.

General.—When used as self-contained sets, driven by engines, belt, or a.c. motors, the machines shown as having separate excitation require an exciter in addition to the main generator. When driven by d.c. motors the separate excitation can be given by the supply circuit.

Commutating poles are generally necessary.

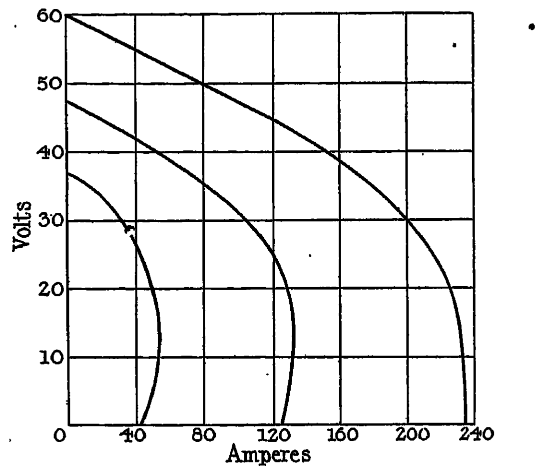


FIG. 12.—Characteristics of Westinghouse (American) welder.

Entirely laminated magnetic circuits improve the regulating action. The adjustments to suit different welding currents are made on one or more of the exciting windings.

An exhaustive paper on "The Design of Constant-Current Generators for Arc Welding," by Mr. K. L. Hansen, appeared in the *Transactions of the American Institute of Electrical Engineers*, 1920, vol. 39, part 2, p. 1357.

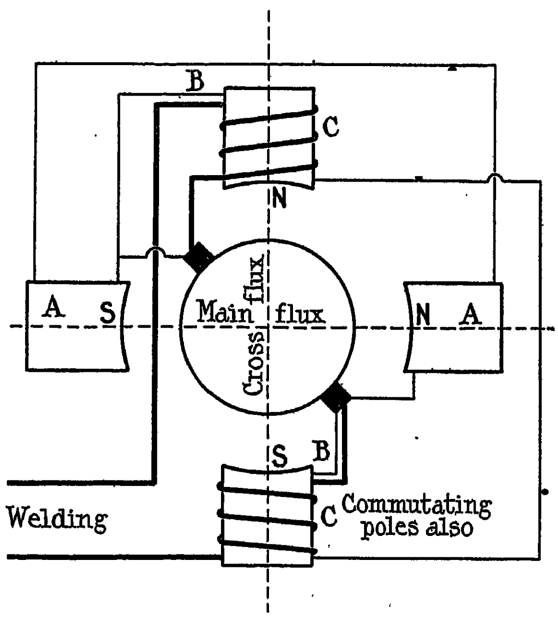


FIG. 13.—Connections of General Electric (American) welder.

Balancer welding machines, dividing the supply current into motor and welding current, with various

arrangements to produce the welding characteristic, have been used, but the general objections to welding direct from a public supply are not removed by their use. They are less wasteful than the stabilizing resistance needed to take up the difference between the welding and the supply voltages.

External field regulation.—Designs of automatic regulators using the welding current to act on the generator fields have been proposed, but do not appear to be in use. The American Westinghouse Company supplies a "flat compounded" machine with a panel adjustment of the series and commutating windings, which appears to regulate by armature reaction effect.

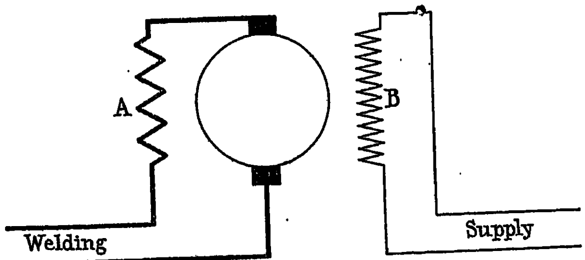


FIG. 14.—Connections of reversed series, separately excited welder.

Regulation by drive.—The only example known to the author is the Davies-Soames set. The connections are as shown in Fig. 16.

A magnetic clutch is interposed between the driving motor and the generator. There are three windings on the clutch magnet: A, separately excited; B, in series with the welding circuit; and C, shunt-excited by the generator.

Winding A predominates normally. Windings B and C both oppose A. When the welding current in

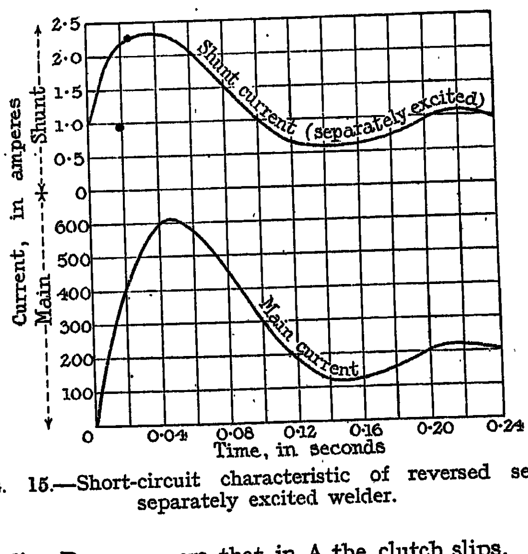


FIG. 15.—Short-circuit characteristic of reversed series, separately excited welder.

winding B overpowers that in A the clutch slips. The welding current is adjusted by rheostats in circuits A and C. Winding C also weakens the clutch magnet to slipping point if the generator voltage becomes excessive.

The generator is compound-wound. The shunt winding is separately excited from the supply circuit, and the series winding is cumulative, not reversed. If driven by an engine or an a.c. motor an exciter is necessary.

A characteristic curve is shown in Fig. 17. In this figure E represents the welding current for which the set is adjusted.

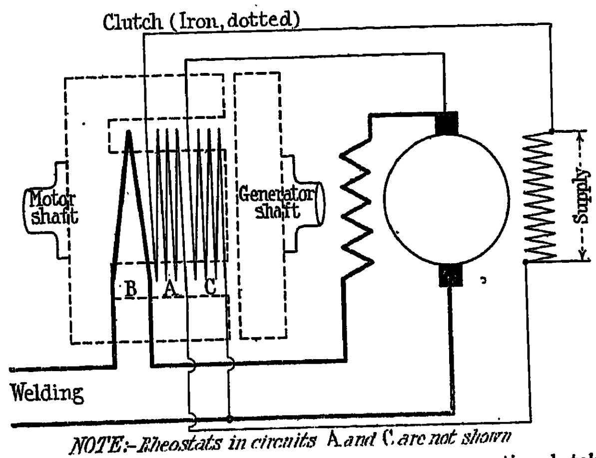


FIG. 16.—Connections of Davies-Soames magnetic clutch welder.

(8) DIRECT-CURRENT MULTIPLE-WELDER SETS.

Generators to supply a number of welders should give constant voltage at all loads from zero to the simultaneous maximum demand of all the welders. As the fluctuation of load is extremely violent the self regulation must be very prompt. Compounding should cover the voltage-drop in the mains as well as the variation of speed with load in the driving motor. Separate excitation and a quick-acting automatic regulator in the shunt circuit are advisable, and commutating poles are essential. It will lessen the risk of mutual interference by the welders if a rather higher voltage than 60 is provided.

Multiple welders in general are "flat compounded"

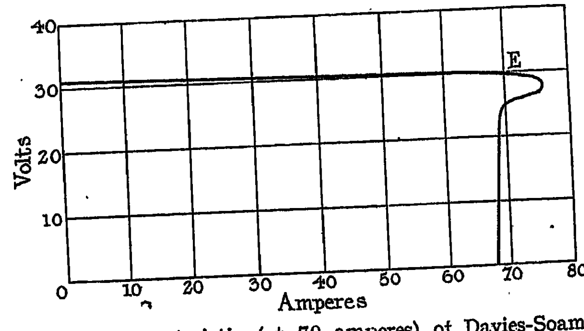


FIG. 17.—Characteristic (at 70 amperes) of Davies-Soames magnetic clutch welder.

machines, with commutating poles. The regulation for each welder is effected by separate resistances. The welding circuits are all in parallel.

The Wilson equipment has a carbon-pile resistance with a solenoid in the welding circuit acting against a spring which compresses the pile. The adjustment

is made by shunts on the solenoid. This machine is made as a single or multiple welder.

One American company makes a constant-current series multiple welder, in which the individual welder adjustments are made by shunts on the main line. When welding is not in progress the shunt is short-circuited. The machine regulates for constant current, and variable voltage, much as a series arc-lighting machine. The machine seems only suitable for factory use on bench work where the work can be insulated and is of a fairly uniform character.

Performance and testing.—A satisfactory characteristic obtained by the usual method of varying the circuit resistance does not prove that a machine will be satisfactory for welding. In welding, the transient effects of load variations are important and are not shown by the usual tests. The rapid fluctuation of a welding load is a severe test of commutating qualities. The only satisfactory test of a welding set is to make good welds with it, using the different current values which will be required in actual work.

Stabilizing rheostats.—There is a somewhat general opinion among welders that the stabilizing resistance in direct-current welding are improved by the addition of a certain proportion of reactance. Evidently reactance is calculated to reduce the rate of current fluctuation, and particularly to reduce " sticking " on striking the arc. Such reactances must be adjustable for different welding currents, and obviously must include air-gaps. It seems more logical to provide the reactance in the generator itself, particularly in the form of armature self-induction. Flux-covered electrodes give smaller fluctuations than bare electrodes and at least reduce the need for external reactance.

(9) Welding-circuit Regulation.

Each welder requires a resistance which he can adjust to pass the current required by the work in hand. It is generally stated that this resistance should include some reactance, as the amplitude of current oscillations is thereby reduced. Evidently the reactance should also be adjustable to suit the working current. Reactance probably assists in striking the arc, as it chokes down the current-rush on making contact, and adds a little to the circuit voltage as the contact is broken. Such reactances must have air-gaps, which may be adjustable to suit various currents. One device used to assist the arc striking is an automatic switch which cuts out some resistance as soon as the arc starts.

These resistances have to dissipate from 1 to 6 kW each as long as welding is being done. They are therefore more bulky and expensive for their capacity than starting resistances and the like which are only in use intermittently, and a much more liberal design is necessary. They have to be located within reach of the welders. It is therefore worth while to pay attention to their design in respect to working temperature, ventilation, bulk and protection. The grid form is robust and convenient if made with steel units, otherwise coils are to be preferred. A tapered resistance, i.e. one in which the cross-section is reduced at the successive taps, saves material as compared with a uniform section of resistor. Usually the welding lead terminates in a plug inserted into sockets connected to the taps. Some resistance material could be saved by arranging for sections to be connected in parallel and series combinations, but this would require some form of controller, with doubtful net saving. A finer adjustment than that provided by the taps is sometimes used, and this is advantageous for the finer classes of work. Squeeze-up carbon piles are not suitable for the main resistances, as their resistance changes too much with temperature, and they do not give sufficient range. They are, however, fairly satisfactory for fine adjustment. Evidently, where welding equipments are intended for uniform work, a lesser range of current adjustment is needed than where the work is of a varied character.

(10) Alternating-current Sets.

It may be assumed that alternating current will always be taken from a public or works general supply and transformed to the welding voltage. Whilst the current fluctuations on the supply side will be reduced in the transforming ratio, they may still be considerable in the view of the supply undertaking. Welding is a single-phase load with a lagging power factor, and the supply engineer will naturally want to be consulted as to the arrangements. If the supply is three-phase the welding current disturbs the balance of the phases. This can be met to some extent where a number of welders are in use, by dividing them between the phases, or single-phase current can be taken from a three-phase transformer by the well-known method of connecting the secondaries in series with one winding reversed. This equalizes the currents in the primary phases, but in two of them the currents are 60° out of phase, one leading, and the other lagging. It is for the supply undertaking to decide which is the less objectionable, and the user should agree with them at the outset.

Alternating-current welding requires 75 to 90 volts on open circuit. The difference between this and the arc voltage is taken up by means of a reactance in the circuit.

The equipment for a.c. welding is therefore a transformer, to give 75 to 90 volts at the secondary terminals on open circuit and to carry the maximum welding current required for the work to be done. An adjustable reactance takes the place of the resistance used with direct currents.

The capacity of single-welder sets for a full range of welding is 12 kVA. For multiple-welder sets the transformer capacity may be less, say from 6 to 8 kVA per welder served.

Whether anything is to be gained by using a multiple-welder transformer as against a separate transformer to each welder depends mainly upon the distribution of the welders in the particular case considered. If all the welders are in one shop so that the secondary leads are short, the saving in transformer cost may be worth while. If they are widely distributed over a large factory or shipyard the cost of the long secondary leads may easily outweigh the saving on the transformers. Single-welder transformers may advantageously be designed with an internal reactance which reduces the amount of external reactance that has

otherwise to be provided. There may also be a saving in the cost of current effected by the reduction of the total iron losses if single-welder transformers are used. Each case has to be considered on its own conditions.

The open-circuit voltage required for a.c. welding may, in some working conditions, be dangerous. The Home Office has for this reason objected to a.c. welding in some exposed positions. To prevent this danger, apparatus has been devised which reduces the open-circuit voltage to 25 volts and also facilitates the striking of the arc.

A fixed reactance does not produce the drooping characteristic desirable for arc welding in the sharp way necessary; the choke should increase very rapidly if the desired current is exceeded. Several forms of a.c. single-welder apparatus are described below:—

(*a*) *Ordinary transformer*.—For a complete range of work the output of a single-welder transformer is 200 amperes at 60 volts, with an open-circuit pressure of from 75 to 90 volts, depending somewhat on the class of work to be done. This implies considerable internal reactance. It is convenient to have tappings at 5-volt steps to allow for conductor resistance and for variation in the electrodes and stock metal. An adjustable reactance with sockets to take the electrode plug is required for current adjustment. With this simple equipment good work can be done and the set can be used in any part of a factory, shipyard, etc., where the a.c. supply is accessible.

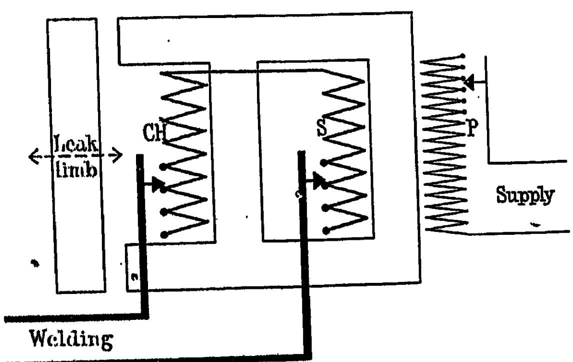


FIG. 18.—Connections of Holslag welding transformer.

(*b*) *Holslag welding transformer* (*The A.C. Cutting and Welding Company*).—This transformer has a third winding in addition to the primary and secondary windings, which is put on a separate iron limb connected to the main yokes, and an unwound limb stands between the common yokes with an adjustable air-gap (see Fig. 18). It is a combined transformer and choke coil, but with mutual inductance and a common leakage path between the two elements. Provided with tappings on primary, secondary and choker windings, and the adjustable leakage path, many combinations may be made. The inventor claims for it a wide range of welding utility. The mutual inductance between the choker and the transformer windings is stated to stabilize the circuit more effectively than an independent choker. Sets are made up for one-, two- and three-phase supply. A description of the device and its theory will be found in the *Transactions of the American Institute of Electrical Engineers*, 1920, vol. 39, part 2, p. 1435.

(*c*) *Davies-Soames automatic regulator* (*Daysohms, Ltd.*).—This apparatus resembles a wound rotor induction motor. The stator and rotor windings are in series, and are of equal numbers of turns. The rotor is free to rotate within limits against certain restraints. In the no-load position the windings produce nearly co-axial opposed poles and magnetomotive forces in the iron, with a minimum reactance. When current is passing the rotor tends to rotate in the direction increasing the resultant flux and reactance, up to the position where the poles are co-axial and the magnetomotive forces are added. This is the position of maximum reactance. With 2-pole windings the angular movement from minimum to maximum choke is obviously 180°. The rotation is opposed by a spring, the force of which can be regulated and damped by a dash-pot. The minimum choke can be regulated by an adjustable stop which limits the rotor movement in the direction given by the spring.

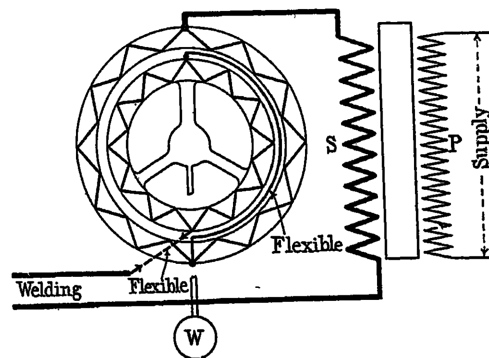


FIG. 19.—Connections of Davies-Soames automatic regulator.

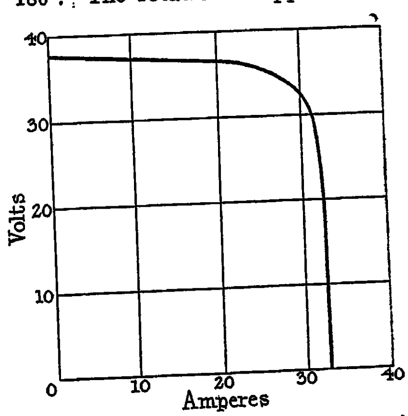


FIG. 20.—Characteristic (at 25 amperes) of Davies-Soames automatic regulator.

To adjust the regulator for welding, the spring is regulated for the desired welding current, and the stop is fixed for the choke corresponding to the arc-striking current. The open-circuit voltage is that of the transformer but on striking the arc the circuit voltage drops instantly, due to the operation of the choke, and the rotor moves until the current torque is balanced by that of the spring. In practice it is found that this regulator gives a very nearly constant current, viz.

that at which the rotor and the spring torque just balance, with a very sharp voltage-drop if that current is exceeded. This drop is not dependent upon the movement of the rotor. As the voltage can only increase sensibly with a decrease in the current, a long arc cannot be maintained, being extinguished by the current-drop. Fig. 19 gives a diagram of the arrangement, a weight being shown instead of the spring actually used; and Fig. 20 shows a characteristic curve of the performance.

The latest form of this alternating-current arc welder embodies the same principle, by which the striking and the welding current are separately adjustable, and consists of a transformer and choke coil in one unit, the choke coil being, as before, provided with a dashpot and adjustable stops to limit the movement of its keeper, and a spring to return it towards zero, which will give the full range of 25 to 200 amperes in infinite gradation. This unit is arranged for direct connection to any alternating-current mains, and as it weighs only about 3 cwts. and is fitted with castors, it is very easily moved about a works.

(*d*) *Alternating-current welding safety device* (*Daysohms, Ltd.*).—Fig. 21 is a diagram of this apparatus,

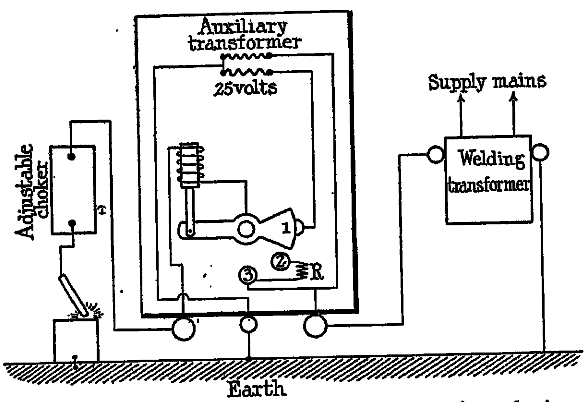


FIG. 21.—Connections of Davies-Soames safety device.

with the connections. In addition to the main or welding transformer there is an auxiliary transformer the secondary of which gives 25 volts, and the work is connected to one end of each of the two secondaries. The electrode lead passes through a solenoid, the core of which pulls on a switch lever. With no current passing and the core down, the switch connects the electrode to the other terminal of the 25-volt secondary, so that the open-circuit voltage between the electrode and the work or earth is 25. On touching the work with the electrode to start the arc, the core is pulled up and the switch moved, first to an intermediate contact connecting to the main transformer through a resistance, and then to a third contact which cuts out the resistance, the switch breaking from the 25-volt terminal just before the third contact is made. The additional resistance at the moment of striking reduces the current-rush and so prevents sticking. When the arc is broken the core drops back and the welding transformer is disconnected from the electrode. It is understood that the Home Office accepts this device as removing the shock danger from alternating-current welding.

(11) Copper, Brass and Bronze Welding.

As the result of recent research work, three types of electrodes are now available for the purpose of welding and depositing non-ferrous metals.

The perfection of these products to a commercial stage represents the latest development in the successful application of electric arc welding for construction and repair.

The metal core is of tinned copper, surrounded by a flux covering, which adheres firmly to the welding rod and does not break away when subjected to transport and workshop usage. This flux covering is of special composition to suit the nature of the copper alloy to be welded, and produces a powerful reducing atmosphere around the work to ensure the deposition of good metal in the weld.

Copper and the various alloys of brass and bronze in general use have a very short temperature-range between the welding and fusion points, and practice is necessary to prevent the metal becoming fluid or remaining in a sluggish condition. Care must be taken to prevent the parts being welded from being pierced by excessive heating.

The heat conductivity of copper is very high, and the deposited metal will lose its heat to the work unless this is pre-heated to a sufficiently high temperature. Therefore, when using these non-ferrous electrodes it is advisable to pre-heat the work before starting the welding operation. In the majority of cases local heating along the line of the weld is sufficient, and this may be applied by a blow-lamp. Whenever possible the joint to be welded should rest upon come refractory material, e.g. carbon, asbestos millboard, or furnace lining material.

It is not necessary or advisable to hammer the metal deposited, as this is perfectly homogeneous and free from blow-holes.

The electric current requires to be regulated according to the nature and dimensions of the material to be welded. Once this has been ascertained, however, the welding operation should be proceeded with as rapidly as possible, when no difficulty will be experienced in welding copper, brass and bronze with entire satisfaction.

The author takes this opportunity of thanking the several firms supplying electric arc-welding plant and equipment for granting facilities to gain a knowledge of the apparatus described in the paper. He also wishes to record his appreciation of the freely offered assistance received from Mr. H. M. Sayers and Mr. Langdon Davies, and the co-operation of Messrs. H. M. and F. M. Sayers in contributing Appendix III which has revealed the mechanical actions and the functions of the flux covering of electrodes, in some respects leading up to the determinations of the physical features of the welding arc.

APPENDIX I.

Classification of Flux-covered Electrodes.

Type	Description
(1) Standard	To give a weld strength of 26 tons per square inch.
(2) Special tensile A..	To give a weld strength of 29 tons per square inch.
(3) Special tensile B..	To give a weld strength of 35 tons per square inch.
(4) Cutting	For cutting with the electric arc.
(5) Overhead	For welding in an overhead position, specially suitable for boiler repairs.
(6) Carbon A	To deposit 1·5 per cent carbon steel.
(7) Carbon B	To deposit 1 per cent carbon steel.
(8) Carbon C	To deposit 0·75 per cent carbon steel.
(9) Carbon D	To deposit 0·5 per cent carbon steel.
(10) Carbon E	To deposit 0·25 per cent carbon steel.
(11) High-speed steel..	For depositing high-speed steel on tools, drills and cutters, and for reinforcing. Deposit adjusted to suit type of work.
(12) Self-hardening ..	An electrode providing a hard steel deposit.
(13) Manganese steel..	For depositing 14 per cent manganese steel.
(14) Nickel-carbon steel	For welding nickel-carbon and high-tensile steel.
(15) Electrode for depositing cast iron	Forms a high-quality cast iron which flows readily and is machinable, but should only be used when pre-heating is possible.
(16) Soft iron	For repairing heavy cast-iron structures which cannot be pre-heated; also for work requiring a high degree of ductility.
17) Stainless steel ..	For welding all kinds of stainless steel and iron. Deposits stainless steel of highest quality.
(18) Copper..	To weld and deposit copper.
(19) Brass	To weld and deposit the various alloys of brass required.
(20) Bronze..	To weld and deposit the various alloys of bronze required.

APPENDIX II.

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APPENDIX III.

AN INVESTIGATION OF THE IRON WELDING ARC.

By H. M. SAYERS, Member, and F. M. SAYERS.

The object of the investigations described in this Appendix was to obtain some knowledge of the iron welding arc, with a special view to some indication of the conditions determining the transfer of metal from the electrode to the work, and the state of the metal during the transfer. The experiments have been confined to the alternating-current arc at a frequency of 50 periods per second, that being the available supply.

Testing arrangements.—Optical projection is the obvious way to examine an arc, both visually and photographically, and it permits of some magnification, which is essential with the very short arc that produces a satisfactory deposit.

To get the arc in a fixed position necessary for optical projection and photographing, an apparatus was made which resembles a lighting arc lamp. The electrode is clamped in a holder on a rack which is fed to the work by a series motor through a suitable train of gearing. A brake solenoid connected across the arc checks the feeding speed when the arc voltage is low, and vice versa, so that the arc length is kept approximately constant. There is also a hand-moved regulator in the driving motor circuit, so that the operator has an independent control of the feeding speed and, consequently, of the arc length. The "work" is represented by a strip of plate clamped to the periphery of a circular table, which is geared to the driving train and revolves at a speed proportional to the electrode feeding speed. The electrode is horizontal, while the "work" strip is vertical and part of a cylinder. A long camera is mounted to one side with some freedom for swinging about a vertical axis passing approximately through the arc, so that the best aspect of the arc can be chosen, and small variations in its position followed by the observer at the screen end. A shutter rotated by a synchronous motor is fitted between the arc and the camera lens, and the stator of the motor is rotatable about its own axis so that the phase at which the arc is imaged can be varied. For photographing purposes there is fitted to the screen end of the camera a plate holder adapted for use with either a stationary or a falling plate. The magnification obtained is about 4 diameters, and the falling-plate speed such as to give two complete periods (1/25 second) in about 3 inches,

so that two periods are obtained on a quarter plate. The arrangement permits of spectroscopic observation of different parts of the image.

It will be seen that the position of the electrode and work is that of "vertical" welding. As only alternating current is available all the work has been done with covered electrodes, some types of which were found to work much better than others. The criterion for this work is that with the mechanical feed the arc shall be maintained steadily for the useful length of an electrode, i.e. about 16 inches. As this is consumed in rather less than a minute there is only just sufficient time to observe or photograph when there are no interruptions of the arc.

For recording the arc voltage and current curves a small oscillograph was made, with a falling-plate camera, which gives also two periods on a quarter plate.

Supply conditions.—The supply conditions were adjusted by some preliminary trials until the deposit proved good, and were subsequently kept constant. The frequency is 50 periods per second, the open-circuit voltage of the welding transformer about 68, the steadying impedance is partly a choking coil and partly a resistance, the electrodes are No. 14 S.W.G. closely wound with asbestos yarn coated with a flux compound, kindly supplied by Messrs. Alloy Welding Processes, Ltd., and the current is approximately 30 amperes.

General appearances.—Observing the magnified image on the screen with the shutter stationary, one sees that the surface of the work is hollowed and rippled, the ripples being roughly concentric and moving outwards towards the rim of the crater. The crater surface appears to be of clean, molten metal. Surrounding it there is a red-hot rim of matter in ebullition, presumably molten slag. At the end of the electrode the covering melts with a steady rotation at the rate of four or five revolutions per second. At each rotation one turn of the asbestos yarn is removed. The molten covering forms drops at the lower edge of the electrode, parts of which fly across to the work at frequent intervals. The path appears to be outside the vapour body.

The arc or vapour mass is of no very definite or constant form, and rapidly changes shape. At the electrode end it appears to be of rather larger diameter than the electrode, and apparently an overlap of it rotates and removes the covering, as described above. It narrows at the work end and seems to terminate on a very bright part of the crater on the work, a patch smaller than the electrode diameter, and of irregular and changing shape. Between the two the arc expands, a good deal on the upper side, but not so much on the lower side. It gives the impression that, but for the effect of gravity, it would take a spherical shape, but with a somewhat large segment cut off by the electrode boundary. The colour of this arc is a blue-violet, and there is no appearance of any drops or particles traversing it. To the eye it is not brighter than the electrode and work surfaces, but the colour of the latter is bright red to orange, or nearly white, while that of the arc is blue, as stated. Photographed without any colour screen, the arc is far brighter than anything else excepting the bright patch where it seems to terminate on the work crater. It has not been possible to see the actual electrode end, as the flux covering masks it, suggesting that the metal surface is decidedly within the edge of the covering.

Photographed on a dropping plate (with the shutter open and stationary) the arc shows as two bright patches per period. The width of these patches corresponds to about two-thirds of an alternation; and they are brightest in the centre, shading off to a sharp edge. The image of the bright spot on the work crater is nearly continuous but is not so bright.

Observed visually with the synchronous shutter and a certain position of the stator, the appearance is not materially different from that obtaining with no shutter. On rotating the stator, i.e. altering the phase of the shutter opening, the blue vapour mass fades and finally, for a space centred on a 90° angle from the maximum arc size and brightness, the vapour mass disappears. The electrode end and the work crater surface are seen glowing, and the surrounding slag boiling, the inference being that the arc is extinguished, or the blue vapour mass non-existent, for a definite interval on either side of the zero-current points.

Oscillograms.—Oscillograms have been made, using the falling-plate method. The open-circuit voltage is approximately sinusoidal. The voltage curve with the arc established has much steeper sides and a broad two-peaked maximum. The arc-current curve is a triangular peak with a base of about two-thirds the duration of each alternation. The other third is at zero value. This duration corresponds to the falling-plate photograph of the arc, and appears to mean that the current passes only while the vapour body is in existence. Presumably the current is interrupted and the arc stops at some point in the descent of the voltage, and both are re-established on the following reverse rise of the voltage. It is clear that the arc duration in each alternation corresponds to that of the peak of the voltage curve, the valley between the two peaks of the voltage maximum to the rapid rise of the current, and the rise to the second peak to the rapid fall of the current.

At the time of preparing this Appendix no calibrated measurements have been made of these oscillograms, but it is hoped to make some in subsequent work.

Spectroscopic appearances.—Only visual observations have been made with a small direct-vision spectroscope. These show a bright-line spectrum of the arc body, which seems to be chiefly the arc spectrum of iron, though the sodium D line is strong, doubtless from the flux composition. Satisfactory observations of the electrode and work spectra during the periods of arc extinction have not yet been achieved. It is hoped to improve the apparatus sufficiently to succeed in these, and perhaps to obtain spectrographs photographically.

Temperature distribution.—With an image of the arc in a nearly stationary position on a screen it seems possible to investigate the temperature distribution by a thermopile or other means of measuring radiation. This has not, however, yet been attempted.

Method of transfer of metal.—The observations made do not justify any decisive statement as to the way in which the iron is transferred from the electrode to the work. They seem, however, to indicate that the arc body is chiefly iron vapour at a temperature consider-

ably above the melting point of the metal. It is possible that this vapour body sheathes and masks a stream of very fine droplets of molten iron, but so far nothing of the kind has been observed. The molten flux-covering does visibly pass from the electrode to the work in fairly large drops, but, as above stated, outside the arc, and below it in this case of vertical welding. The current oscillograms are symmetrical above and below the zero line, i.e. they indicate no difference due to the reversing polarity of the electrode and the work.

It would obviously be easier to observe any such difference as shown by the arc image with direct current, and it is recognized that the investigations described are incomplete without working on direct-current welding arcs.

Quantity of deposit.—One of the measurements which it is hoped to make with the help of the apparatus described is the quantity of iron deposited per unit of current and time, or per unit of energy in the arc. This again should be observed with both alternating and direct currents, and with varying electrode sizes and currents.

The literature of the subject contains a number of statements on this point, but they vary so widely that one can only suppose that they are made under widely varying conditions and are not comparable. Mr. Langdon Davies has kindly furnished some results of tests made by him. With a No. 8 electrode and direct current he found a deposit of 157·8 grammes per kilowatt-hour, the energy being measured at the input side of a motor-generator. With alternating current he obtained with the same size of electrode a deposit of 315·5 grammes per kilowatt-hour when the open-circuit voltage of the transformer was 55; and 351·0 grammes per kilowatt-hour when the open-circuit voltage was 45. The energy measurements in this case also were made on the input side of the transformer. As the energy includes the converting and transforming losses it is obvious that the deposit per unit of arc energy must be higher. The greater weight per kilowatt-hour with alternating current is naturally due to the fact that the motor-generator losses were much higher than the transformer losses. The improvement in depositing efficiency due to reducing the open-circuit voltage from 55 to 45 of course means smaller impedance losses between the transformer and the arc. These figures appear to suggest that the deposit per kilowatt-hour of arc energy is of the order of 800 grammes. Measurements with a considerable number of current values and electrode sizes will be necessary to establish the figure, which is hardly likely to be a physical constant in any sense. If it is the case that the iron is transferred as vapour, then there is a limit fixed by the vaporization heat of iron. Having found no record of a determination of this quantity, the authors cannot say what such limit is. Evidently, however, not all the iron volatilized at the electrode is deposited on the work, and the losses by oxidation, condensation, etc., are likely to vary to a large extent with the working conditions. Thus the oxidation losses should be higher with small electrodes than with large, supposing similar current densities, as the ratio of the surface to the mass of the vapour or arc body is greater in the case of the smaller electrodes and currents.

It may be observed that one instrumental difficulty in measuring the arc energy is that there are no integrating meters on the market for voltages in the neighbourhood of 20 volts, and an integrating meter (or the integration of voltage and current oscillograms) is the only practicable way of measuring the rapidly fluctuating energy in a welding arc.

Conclusion.—The authors cannot claim to have given definite answers to the question: What are the physical conditions of the iron welding arc? They have, it is hoped, shown ways by which some partial solution may be reached, and, if circumstances permit, they hope to pursue the inquiry with improved means and thus obtain some results of practical utility, and possibly of scientific value.

The work described has been done with home-made appliances, and under the limitations of a dwelling house. With laboratory conveniences and resources more definite results might have been obtained with less expenditure of time and labour.

The authors desire to acknowledge much assistance and encouragement from Mr. Langdon Davies, as well as from Major Caldwell.

Discussion before The Institution, 14 December, 1922.

Mrs. H. Ayrton: I have been interested to see that this paper makes no mention of a back E.M.F. in the arc. When I first took up arc work in 1893, and for long afterwards, the idea that there must be a back E.M.F. at the crater to account for the sudden drop of potential there was practically universal. But from my experiments I concluded that what was called a back E.M.F. was really a resistance—not, as the author calls it, a contact resistance, but the resistance of a thin layer of carbon vapour covering the crater. It seemed to me that the arc exactly resembled the steam that issues from a kettle of boiling water; this is true vapour (and therefore invisible) only for a very short distance from the spout, but further away becomes condensed by cooling into a mist of droplets. In the same way the carbon vapour given off by the crater of the carbon arc, which is at the temperature of volatilization, is only true vapour while it is near enough to the crater to remain at that temperature. As successive layers of vapour are given off, the crater recedes further from the earlier ones, which, at some very short definite distance from it, must drop below that temperature and cool into a mist of droplets or particles—probably the latter. The vapour and mist column form the arc proper, sheathed in a flame due to the burning of the mist in contact with the air. Leaving out of account the small fall of potential at the negative carbon, the resistance of the carbon arc is, on this theory, the sum of the resistances of a thin layer of vapour of high specific resistance and of a column of mist of much lower specific resistance. In free air the cross-sections of the crater, the vapour and the mist are all smaller than they would otherwise be,

owing to the cooling down of their circumferences. Except for modifications due to this cooling, the current alone determines the area of the crater, and this area fixes the cross-sections of the vapour and the mist. Thus, if there were no circumferential cooling, a change of current would, all other things being equal, produce an exactly proportional change in the cross-sections of the crater, the vapour and the mist; and, since the resistances of the two latter are inversely proportional to their cross-sections, the resistance of an arc of given length would be inversely proportional to the current, and thus the P.D. across it would be constant for that length. All this is changed, however, by the skin cooling, which, by making the resistance of the arc diminish more rapidly than the current increases, gives the appearance of a negative resistance, causing the P.D. across the arc to diminish when the current is increased, and vice versa. It is easy to see how this happens. Take r as the radius that a cross-section of the arc would have if there were no skin cooling. Then the actual cross-section is $m(r^2-nr)$ or $mr(r-n)$, where m and n are constants. Clearly $r-n$ increases more rapidly than r, and therefore $r(r-n)$ increases more rapidly than r^2; that is, the actual cross-section increases more rapidly than it would in the absence of skin cooling. But the current is proportional to the uncooled cross-section, and the resistance is inversely proportional to the actual cross-section. Therefore the resistance diminishes more rapidly than the current increases. How much of the preceding applies to metal arcs I do not know, but it is worth while bearing in mind when experimenting with them. With regard to the transfer of material from one electrode to another, I have seen this happen in two ways in the vertical direct-current carbon arc. Sometimes small pieces break off the positive and drop on to the negative, or break off the negative and are carried by convection currents to the positive. This is accidental, but the second way is essential. When a fairly short arc is suddenly further shortened, a white-hot cap grows on the tip of the negative carbon, lengthening it for a short time. If hissing supervenes the cap grows into a "mushroom"; if not, it shortly disappears. The cap is mist, condensed by the sudden transference of the tip of the negative from a cooler to a hotter place. For a short time the negative retains the lower temperature and the mist in contact with it condenses. Only a short arc has a sufficiently steep temperature gradient for this to happen. As the mist was originally crater vapour this is a genuine case of transference from positive to negative, but it only occurs in the above special circumstances. There is much to be said on the point, but it would be out of place here. The transfer of material with metal arcs is altogether another question. Here, as the author points out, the vaporization is from a molten metal crater instead of from a solid one; in addition, the negative may easily be melted under the roasting of the crater, and so rendered particularly easy of transference. I would suggest that the superiority of the short arc in welding is due partly to the deep crater that a short arc always entails, making "penetration" easy, and partly to the negative being melted owing to its proximity to the crater. With an alternating-current arc this applies even more strongly than with direct current, because in this case as each electrode is positive in turn they must both necessarily be all the time in a molten state, and therefore easily transferable. May not this be the reason why Mr. Langdon Davies found that an alternating-current arc deposited practically twice as much per kWh as a direct-current arc? The deposit would probably be even greater with more rapid alternations. Half a dozen problems lie in this question alone. The author's paper shows that the metal arc offers a wide and fascinating field for research, and it is to be hoped that Messrs. Sayers will be able to continue their careful and well-thought-out experiments. Indeed, there is room for many investigators in a subject which promises such varied and rich results, both scientific and practical.

Mr. H. M. Hobart: During the past 5 years flux-covered electrodes have been almost exclusively used in this country, and no progress has been made with the introduction of the bare electrode. I consider that the author has made out a very good case for the use of flux-covered electrodes for the highest grade work. It is interesting to realize that in this country during the last 24 hours there have been melted up several hundred thousand feet of electrodes in making electric arc welds, and that during the same period in America a more or less similar quantity has been used. At least 95 per cent of the work in America has been done with bare wire, while in Great Britain flux-covered electrodes have been almost invariably used. During these past 5 years each country has known what the other has been doing, and each has been going its own way in the comfortable belief that its own method was preferable. I should like to point out the importance of different countries keeping in close touch with one another in their researches. For instance, British welding engineers are already satisfied that the use of the flux-covered electrode is correct in the majority of cases, and, consequently, although the paper is instructive it is not nearly as useful as it would be if it were presented in America. In the same way some American authors have shown to the satisfaction of almost everybody in America that the bare electrode is preferable; they say that the flux covering interferes with good work and involves greater cost. They also say that the bare electrode, in the hands of operators who know how to use it, gives the best results. If studied in this country it might be found that there is a field for the bare electrode in arc welding.

Dr. C. Sharp: I should like to say, as a member of many years' standing of the American Institute of Electrical Engineers, that it gives me very great pleasure to attend a meeting of this Institution. I have never heard a more interesting, a better presented and more instructive paper on electrical welding. We all wish to effect a more intimate tie between England and America, and to accomplish this result no means are more effective than electrical means.

Mr. C. R. Darling: Some years ago it was my privilege to preside over an Electric Welding Research Committee, which was under the auspices of the Admiralty. There I worked with Major Caldwell and others, and we kept in touch during the whole period

with the corresponding committee in the United States. We certainly learned something from them, and I hope that they learned something from us. I quite agree that international research is very desirable. Very great advances have been made during the past few years in equipment and similar matters, but we do not seem to have got much further towards a proper understanding of the nature of the iron arc. Surely this question of fluxing the electrodes could be worked out and proved one way or the other. It seems extraordinary that in America 90 per cent of the work is done with bare electrodes at a cost much less than that in this country where flux-covered electrodes are used. It surely should not be difficult to discover whether an equally good weld cannot be obtained with bare wire; it is only a matter of having welds made by competent operators and testing them. A firm which possesses a research laboratory could take the two types of electrodes, make welds and test them to see if those produced by one method are as good as those produced by the other. Again, no mention has been made of the chemical side of the problems of arc welding. I have frequently seen welds made by the same welder on two pieces of plate cut side by side from a large plate with the same electrodes, but the tensile strength of one weld would be about 27 tons per sq. in., while that of the other one was only about 19 tons per sq. in. These differences are attributed to the presence of sulphur or occluded gases but were never properly explained. These points also could be cleared up by the research department of a firm, with the result that ultimately we should be able to put electrical welding on a much better basis, which would be all for the good of the work. In conclusion, I should like to refer to the projection of the material across the arc. In the case of an overhead weld the iron rises vertically from the electrode and is deposited on the work overhead, although the condensed vapour is heavier than air. The fact must always be remembered when discussing any theories of electrical welding. That is, I think, what the author meant when he said that there was definite projection.

Captain R. J. Wallis-Jones: The author states that owing to the war conditions the use of arc welding was very greatly extended, but I think one may say that electric arc welding was almost re-invented during the war. The paper is an excellent review of the present position of the arc with regard to electric welding. Further, it indicates the matters upon which further investigation is needed. I refer particularly to page 255, where the author asks: "In what state does the iron cross the arc?" Dr. Elihu Thomson, in a recently published article in the *Encyclopædia Britannica*, gives his view on that point as follows: "In operation the arc voltage may be from 10 to 20 volts, and the current traversing the arc may be from 80 to 200 amperes or more. The welding is attended by much spluttering and projection of fused and superheated globules of iron from the end of the wire electrode towards the cooler and heavier masses of the work pieces; in fact, the deposition of metal on the work is possibly due to a jet of iron vapour from the electrode wire carrying fused iron globules as a result of explosive boiling of the iron." The author also asks what is the distribution of voltage-drop in the iron arc, and what are the quantitative relations to electrical and other variables of this transfer of metal. I feel quite sure that we shall get some very useful information on these three points in the future. The author, later in the paper, refers to the use of alternating current, and the danger of shock. I think it is not fully realized how very dangerous it is under certain conditions to get a shock from a comparatively low-voltage alternating current. The Memorandum on Electric Arc Welding issued by the Home Office Factory Department states that in six years the number of fatal accidents from electric shock at 250 volts or less was 98 on a.c. circuits (one being from a welding set), and none on d.c. circuits. As pointed out by the author, fortunately at the present moment there are at least two devices which automatically limit the voltage, so that it is quite safe to weld in even such an undesirable place as the interior of a boiler. The author also refers to automatic arc-welding machines as being barely beyond the experimental stage. There are, however, two machines at present available, one of them being designed by the General Electric Company. It has an endless electrode, which is moved upwards and downwards by means of a motor actuating rolls which grip the electrode; the regulation is so perfect that the arc has, I understand, been operated for no less than 16 hours without interruption. It is claimed for this machine that it is very adaptable for welding thin sheet down to, say, No. 26 gauge. Another American machine, the Lincoln automatic arc welder, uses a carbon electrode, and the regulation of the length of the arc is also controlled by a motor. The traverse of the arc over the work is actuated by another small motor. I have seen samples of work said to have been done by this machine and they are very good, especially on thin material. The author refers to the fact that welding on thin sheets, etc., has not been very largely carried out by means of the arc process, possibly owing to the competition of oxy-acetylene welding and resistance methods. I should like to quote one or two figures of the rate of welding by the Thomson or resistance method. In the case of seam-welding two pieces of steel plate 0·036 in. thick, at the rate of 6 ft. per minute, such a seam 24 ft. long would cost 1d. to weld, for the energy only, when the cost of energy is taken at 1d. per unit. In spot-welding sheets of an added thickness of 0·16 in. at a speed of 70 spots per minute, 400 spots can be welded at a cost of 1d. with energy at the same price. These are fair figures. The very interesting apparatus which Messrs. Sayers have designed will, I feel sure, give much more information in the future about the action of the arc. In conclusion, I should like to say a few words in regard to the war services rendered by the author. While at the Admiralty, owing, I believe, first to the difficulty of getting oxygen for acetylene welding, the attention of the authorities was turned to the possibilities of arc welding. At that time the submarine menace was very serious, and therefore anything that could be done to facilitate the repair of shipping or to aid in the construction was of the greatest national importance. Major Caldwell did much valuable work for the Admiralty; he also visited America and, in collaboration with Mr. Hobart, did immense service

in finding out what could be done to increase the use of electric welding. I should like to ask the author if he would be good enough to present to the Institution Library two books which he wrote at the time. The first is "Reports on Electric Welding and its Application to Ship Construction," United States Shipping Board (Emergency Fleet Corporation), and the other is the "Report on Applications of Welding to Ordnance Construction."

Mr. W. McClelland: As a colleague of the author at the Admiralty, I should like first to associate myself with Captain Wallis-Jones's remarks in regard to the valuable work which the author did during the war. He set up an organization and trained men all over the country, with the result that much very remarkable electric welding work was accomplished. As an example, a ship came into one of the shipyards very badly holed at the bottom, and it was necessary that she should be repaired quickly. The ordinary time for repairing that ship by riveting would have been 3 to 4 months, but with electric welding the ship went out to sea in 3 to 4 weeks, and for 18 months after that crossed the Atlantic to and fro regularly without a break. At a later stage the author assisted the U.S.A. authorities in regard to the development of electric arc welding for shipbuilding purposes. On page 253 he says: "Arc-welding practice is in advance of theory." He knows full well why this is so; it was absolute necessity; the development during the war was one almost of trial and error-elimination. It seems to me that the ideal electrode for welding should provide a molten vapour stream enclosed in an inert gas. The interesting experiments shown by Mr. Sayers this evening demonstrate that with the short arc the molten stream is enveloped in the molten flux from the flux-covered electrode. I think that is a very important point, and indicates a great advantage of the flux-covered electrode over the bare electrode. I should like to ask the author whether the experiments referred to in Appendix III were made with makes of electrodes other than the Alloy Welding Process electrodes, and, if so, whether he could tell us what makes and with what results. On page 255 he refers to the voltage, which he considers would produce what might be termed "porosity" defects. That again is, I think, a question of the particular electrode used. My experience is that this voltage with flux-covered electrodes would be from 35 to 40. As regards choice of current, it seems to me that, apart from the question of general distribution of alternating current, alternating-current welding has very few advantages. As to direct-current versus alternating-current welding—I say this with all deference to the experiments shown to-night and to what Mrs. Ayrton has so kindly stated—a.c. welds do not seem to be so uniform or so consistent in mechanical strength as d.c. welds. Certain tests which were carried out some time ago on steel plates with various classes of joints showed definitely that the d.c. weld was much superior to the a.c. weld. With alternating current, difficulty is sometimes experienced in establishing and maintaining the arc under a pressure of 90 to 100 volts, particularly at a low periodicity. The question of a.c. shock at this pressure to operators wearing coloured glasses and working on narrow staging at considerable heights on the side of an "earthed" ship in dry dock, is a serious one, and the automatic a.c. set referred to on page 263 appears therefore to be an interesting and useful development. With regard to the generator design, I am not sure that the importance of the automatic machinery for the production of a satisfactory weld has not been rather overstated. The author has furnished an excellent statement indicating the types of welding machines at present on the market. My experience for shipyard work is that the d.c. multiple welding set with a flat-compounded generator giving probably 60 to 70 volts when worked by a skilled operator produces satisfactory and consistent results. This type of machine is in my opinion the simplest and best to use, particularly where there is a possibility of extensions to a welding system, as with such a set one or many operators can work simultaneously quite satisfactorily. For welding work on the side of a ship in dry dock it is hardly practicable to have a portable automatic running machine for each operator; the first cost of such automatic machines would be high.

Mr. E. B. Wedmore: Mr. Addenbrooke suggested to me recently that had it not been for Ohm we should know a good deal more about insulation than we do. Ohm gave us a simple law of resistance. We say that conductivity is the inverse of resistance, and think that we know all about conductivity. I now suggest that had it not been for Mrs. Ayrton we should perhaps know a great deal more than we do about the metallic arc. We are tempted to think that Mrs. Ayrton has told us all about the arc, and we cease from making observations, whereas the success of the welding industry in the future will depend upon the attention given to the properties of the metallic arc. The author has maintained in the paper a very proper balance between our interests in the past and in the future. Whilst bringing to our notice details of the development of a large and important industry, he has devoted a large part of the paper to the subject of research, and the future rests on research. Mr. H. M. Sayers and his son are making a vigorous attack, but with very inadequate facilities, on some of the technical problems urgently awaiting solution. A sum corresponding to the saving already effected in carrying out any one only of the larger repair jobs which have been described to us, would provide the means for a comprehensive and productive research, which should repay the industry manifold. I feel sure that the Electrical Research Association would count it a privilege to place facilities for co-operative research at the disposal of the interested parties.

Mr. H. M. Sayers: I propose first to show three slides in connection with a.c. welding. The first shows the supply voltage, approximately sinusoidal. The second shows the voltage across the arc, and it will be seen that it is very different from the supply voltage. The rise and fall of the voltage are very sharp, and there is a double peak. The third slide shows the arc current. The curve is almost triangular, with a very considerable portion of zero current, and if the current curve is superimposed on the voltage curve it will be seen that the triangular arc peak must correspond to the valley between the double peaks of the voltage curve. I want to point out that the arc makes its own voltage curve,

owing to the minimum voltage required for the arc current. Metal arc-voltage and arc-current curves with alternating current always seem to present these features. I have made some spectroscopic investigations upon the question of how the metal is transferred across the arc, and I find that at maximum current, i.e. when there is a blue luminous arc between the electrode and the work, the spectrum is to all intents and purposes an iron-arc spectrum, which contains a great many bright lines with some dark lines, particularly the dark sodium D line. At the phase of zero current the spectroscope shows other bright lines, i.e. not the iron-arc line. The brightest is the sodium D line. This shows that some of the iron is incandescent vapour. If it were wholly in a liquid state it would give a continuous spectrum, but as it gives a bright-line spectrum, and not a continuous spectrum, the inference must be that some part of the metal is in the state of gas. The fact that the dark sodium line is superimposed on the iron spectrum and a bright sodium line appears during zero current shows that the flux coating containing sodium produces an enveloping sheath round the iron vapour, and probably protects it from oxidation. It also, I consider, fulfils the very important part of forming a conducting bridge, or a bridge which will be conducting as soon as the voltage reaches a certain point and prevents the extinction of the arc during the zero periods. I suggest that, at any rate as regards a.c. work, these two functions of the flux are of the very greatest importance. With the help of Mr. Hamilton Wilson's tiny thermopiles I hope to explore the temperature distribution in the arc by getting radiation measurements in the arc image. As to the quantitative relation between the energy installed in the arc and the deposition, since I wrote Appendix III I have seen a statement in an American journal of the latent heat of vaporization of iron, in terms of grammes per unit of energy, from which 1 kWh should vaporize some 750 grammes. That is rather a lower figure than the 800 grammes which I have suggested. Most of the electrodes used in the experiments described in Appendix III were those of the Alloy Welding Processes, Ltd., and the Quasi-Arc Company. I have had to give more time to getting workable conditions than to making comparisons between different electrodes.

Mr. P. M. Baker (*communicated*): The paper is particularly interesting to me as, during the later days of the war, I was able to make a few observations in connection with welding arcs in the establishments which we, of the Ministry of Munitions, set up to train men and women as operators for the welding work in which the author was then engaged. At that time the view was held that in the d.c. iron-iron arc the transfer of metal from electrode to work was an electrical function (analogous to some extent to the transfer in an electrolytic cell), and a.c. arcs were not, in consequence, favoured, particularly for upright and overhead work. We incidentally found that while it was a quite simple matter to train otherwise unskilled persons to do reliable welding with d.c. equipment in a comparatively short time, the work done by operators, trained on an "intensive" system, with a.c. equipment was much rougher and less satisfactory. The author's investigations and experiences seem to show that our ideas as to the force propelling the metal across the gap were wrong (we never held them very strongly), and he seems to favour the view that it is a thermal function—the metal travelling from a hotter to a cooler body. I should like to suggest that it may be a function of the difference between the *masses* of the work and of the electrode, respectively. From a scientific point of view this would be an interesting point to investigate, but its practical importance is not very great. In connection with single-welding d.c. outfits it would be interesting to know whether either the excitation or the magnetic clutch method of control acts sufficiently rapidly to maintain the arc current at anything like a constant value. Possibly the author in his reply could give recording-ammeter charts for some of these machines. Referring to the neat devices used by Mr. Sayers, I suggest that the results of his spectroscopic examinations would be of value, and the publication of his oscillograms would be helpful to those who are trying to visualize what happens in the a.c. arc. The two "shoulders" which appeared on the "steeple" of the current wave seem to indicate either a latent-heat effect or a curious resistance-temperature variation in the vapours at the moment of vaporization or quasi-vaporization of the iron. The superposition of the current and voltage oscillograms in correct phase relationship, if available, would probably help to decide which explanation was correct.

Mr. W. H. Flood (*communicated*): The author has brought to our notice the successful development of electrodes for depositing copper, bronze and brass, and I am sure this will fill a long-felt want, as years ago we were asked if we could weld on copper or bronze pipe flanges by the arc process. Now that non-ferrous electrodes are available for this purpose, it will be possible to carry out quite a large number of repairs which have hitherto been next to impossible, e.g. locomotive furnaces, copper vats, etc., which must be repaired in position. I hope that the author will be able to supply us with data on copper welding, and, if possible, show some examples of actual work accomplished. As regards the various types of plant used and recommended by different concerns, the tendency appears to be in favour of alternating current, as the d.c. sets described which, I take it, are the best that designers can produce, are stated to be more or less complicated, and in consequence require a deal of care and skill to adjust in order to extract from them the exacting welding characteristics demanded by the metallic arc, whereas the alternating-current equipments are simple and free from such complications. As electric welding is now looked upon as a commercial proposition, the plant used must of necessity be quite free from uncertainty of action and complex adjusting switches and instruments, as the average welder is neither a mechanic nor an electrician, and, further, he cannot be expected to acquire sufficient knowledge to make delicate adjustments, even though he were so disposed, as in order to acquire the art of good welding he must devote the whole of his time to the business end of the electrode. To fit ammeters and voltmeters to welding sets for the guidance of welders is to my mind not only waste of

money but absurd, as the man cannot possibly view these instruments when he is paying attention to the arc. The same applies to shunt regulators and other hand-operated devices which are found necessary in cases where motor-generator sets are employed. It is quite apparent that the majority of d.c. combinations are only suitable for single operators, and I doubt very much if any shipbuilding or engineering concern would be prepared to install a sufficient number of these sets to meet the demand of, say, from 10 to 50 welders, as my experience of plant of this description is that the possibility of breakdown is always present, and the upkeep of brushes and brush-gear is sufficient to put the proposition entirely out of court. To install one large unit with regulating resistances for each welder is equally bad, as the capacity of the generator must of necessity be more than double that required by the welders, on account of the heavy loss in resistances. Further, the cost of low-pressure cables between the generator and the various welding locations would be a considerable item which no purchaser could afford to ignore. With alternating current these difficulties are removed almost entirely, as the change from high pressure to the welding voltage is made by means of static apparatus, and no further adjustments are required when once the correct values are fixed, and in a well-known type of welding transformer the whole of the regulation required to give the correct welding characteristics is embodied in the design, and self-contained on one core. I refer to the Holslag transformer briefly described on page 263. With this apparatus the operator is not expected to have any electrical knowledge whatever, and, as it is not possible to destroy or burn out the windings during welding or by wilful means, the adoption of this welder is a sound commercial proposition and should find favour. This transformer must not be confused with the ordinary transformer and choke-oil combination, as the design is quite unique, and means are provided for obtaining full control of the correct heat or power required by any size or type of electrode, including bare wire. The transformer and choke-coil combination is analogous to the resistance on direct current so far as regulation is concerned, and its use is a step backwards in the progress of arc welding, as a separate reactance can only subtract from the voltage of the transformer, and such a system cannot supply the voltage regulation corresponding to the current fluctuations in the arc. Oscillograms show that were it not for the heavy flux coating on certain electrodes, a separate reactance could not hold the arc at the voltage employed, which means that there are periods when the molten slag is the only conductor and support for the arc with no iron vapour present, and this condition encourages slag inclusion which is a very bad feature. Also, the proper variation and separation of the voltage factor cannot be obtained with the transformer and separate reactance. The only regulation obtained is that for constant current, whereas the control of power is absolutely essential for melting metal efficiently. For correct welding the power must be kept constant, and means provided for automatically adjusting the voltage instantly the current varies or the arc has a tendency to die out. This is called a "guardian" voltage, and is always present with the Holslag system and ready to act instantaneously when required to support or adjust the power for which the apparatus is set. To meet Home Office regulations this set is fitted with a special safety contactor device operated by a 25-volt winding, which ensures that the operator is protected from all possibility of receiving a shock due to the open-circuit voltage which is considered dangerous. This contactor is operated automatically on striking the arc, and drops out immediately the arc is broken. It will be readily observed that with apparatus of this description there is no limit to the number of units which can be installed, as in the majority of cases works have an ample supply of alternating current and substantial transformers, and by equally distributing the welding sets across the phases the load is balanced within limits, and no complexities, other than those present when the first few sets are put into operation, appear. The efficiency of such a system is good, and as the upkeep of plant is reduced to practically nil I think it will be agreed that the alternating-current proposition is to-day in advance of any direct-current scheme.

Lord Angus Kennedy (*communicated*): In the discussion of the use of flux-covered versus bare metal electrodes it appears to me that sufficient stress has not been laid upon the important part that the flux plays in alternating-current welding by protecting the weld from the air. If welders attempt to use bare electrodes with alternating current, consistently satisfactory results cannot be expected.

Mr. R. S. Kennedy (*communicated*): I consider the paper to be an able exposition on plant and materials as at present available. On page 258 the author quite rightly remarks that the automatic arc welder has not yet arrived. My own experience in actual working has been entirely with direct current, and we find the difference in temperature of the poles to be a distinct advantage. We also find a voltage of 45 on a level-compound machine to be sufficient for our work, and considerably higher currents than 200 amperes can be handled. On the same page the coating of the electrode also is referred to; I prefer a coating that fuses at a slightly lower temperature than the iron electrode, so that the tip is exposed and the man can better watch his work. This is particularly necessary in overhead work. I do not consider that the slag method is an advantage or that it is necessary with fully trained welders.

Mr. H. Ogden (*communicated*): I think that the solution of the transference problem lies in the direction of a consideration of all the forces acting in the region of the arc, for we must admit no mystery in the transference of metal. What are these forces? First, there is gravity and this certainly assists in the transference of metal in downward welding, which is thus made easier than overhead welding. Secondly, there is the "pinch" effect of an electric current and I believe this to be important. In induction smelting furnaces the "pinch" effect causes a rupture in the liquid metal when the current density exceeds a certain value. In the arc I believe that this effect helps to detach drops of molten metal from the tip of the electrode acting against the force of surface tension in the molten drops. Thus this effect creates drops of metal which under

other forces then travel across the arc to the larger pole. The main factor which draws the drops to the work is surface tension coupled with a greater vapour pressure at the electrode tip than near the more massive work. What I have just mentioned deals with the transference of the larger drops which in welding can be seen crossing from electrode to crater. With regard to other forces exerting an action tending in the same direction, there is first the condensation of metal vapour on the more massive work. Owing to the greater thermal conductivity of the latter, the vapour pressure in its neighbourhood must be lower than that in the neighbourhood of the electrode tip, so that the conditions are correct for the vapour wind of which Mrs. Ayrton spoke and a certain, if small, amount of metal is transferred in this way. Another force always present is the electrostatic field, about 100 V/cm, between the poles of the arc. The force of gravity acting on a small drop of diameter r is 32 000 r^3 dynes (approximately). The electrostatic force on the same drop is $r/45$ dynes and thus, when r is less than 0·001 mm, the electrostatic force exceeds gravity and these very small drops would invariably travel to the larger pole where, owing to the geometry of the arrangements, the conditions are not favourable for the production of drops. It has been suggested by Prof. Hudson in America that the liberation of occluded gas is instrumental in assisting the transference of metal, but this does not agree with my observations. A wire freed from occluded gas runs smoother and with less splutter than one with occluded gas. In the projected arc exhibited by Mr. Sayers occasional large drops of metal or slag were flung well to one side. Occluded gas, or gas liberated from the heated flux, is probably responsible for such action, because it must be allowed that such gas liberation acts equally in all directions and must tend to blow metal away from the work. Another view, which at one time held some adherents, was that the metal was carried by the current. As the author pointed out, metal is transferred from the smaller to the larger pole, irrespective of polarity. Further, if the current were responsible for the metal transference there would be some quantitative relation between deposit and current, as in an electrolytic cell. No such relationship exists, and so the idea that the metal is carried by the current must be abandoned. Finally, in my opinion, metal is transferred from the smaller to the larger pole chiefly through the action of surface tension, local differences in vapour pressure and the "pinch" effect of an electric current all acting together. In a second degree it is transferred from the smaller to the larger pole by the action of the vapour wind mentioned by Mrs. Ayrton, and by the action of the electrostatic field on very small drops. Before concluding, I should like to refer to the carbon mist mentioned by Mrs. Ayrton. Violle * has measured the temperatures in the carbon arc, which he gives as 3 500° C. for the anode crater, 2 700° C. for the cathode, and higher still for the arc itself. I believe these observations have been confirmed by subsequent workers, and so it appears unlikely that carbon vapour from the positive pole should condense to a solid particle mist in a region of higher temperature than that at which the vapour came into existence. The clear space and misty region observed so beautifully by Mrs. Ayrton are probably susceptible to another explanation, as similar appearances are observed in the discharge of electricity through gases at low pressures.

* *Comptes Rendus*, 1892, vol. 115, p. 1273.

Mr. D. T. Smout (*communicated*): The paper undoubtedly reveals the great divergence of opinion which it is possible for those interested in the practice of the art to possess. The author has shown, however, that good work can be done with many different types of plant and equipment. As the skill and reliability of the artist is the predominating factor in determining the quality of the work executed, it follows that the average quality of the work done falls short of the best possible. In deciding which type of apparatus and equipment is the best, it is therefore necessary first to take the human element into account, and then aim at developing a plant and system of welding as theoretically sound as possible. To conform to this principle it is advisable to disabuse oneself of the idea that an electric arc welder can be at once a combined electrician, metallurgical chemist, smith, etc., nor should he be expected simultaneously to make various adjustments to plant and perform the art of welding. The essential qualifications of a welding operator should be the capability of maintaining a continuous arc of more or less constant minimum length, and the possession of the faculty for recognizing the phenomenon of burning metal. It is well known that with the methods at present in vogue the metal deposited when the arc is first struck is faulty, owing to the fact that the electrode metal is deposited before any crater is produced in the work. For good work it is necessary, therefore, to deposit the first ½ inch or so of electrode metal outside the "V," and the remainder continuously without sticking and restarting. Given electrodes of uniform quality, and electrical apparatus supplying the correct characteristics, an operator with the qualifications mentioned above is not difficult to find. In considering the question of electrodes, irrespective of the type (bare, thinly coated, medium coated or heavily coated), it is necessary that for perfect work two conditions must be present. First, the quality of the electrode metal, and the quality, concentricity and thickness of the coating should be uniform throughout the length of the electrode, subject to certain reservations with regard to concentricity and thickness of coating. Secondly, the physical conditions of the electrode in close proximity to the arc should remain constant, also subject to certain reservations. With regard to the first condition, from personal observation I have found little trouble on the score of lack of uniformity in the quality of electrode metal, but have found that many types of coated electrodes leave much to be desired as regards uniformity of the coating. One well-known type of electrode in particular invariably reveals a bad spot about ½ inch from the commencement, owing to a failure on the part of the manufacturer to preserve perfect uniformity in this respect. In depositing this particular electrode the arc is invariably destroyed when this bad spot is reached. With regard to the process of covering heavily coated electrodes by means of asbestos yarn, I should like to suggest that

this method does not tend to preserve the stability of the arc. It is well known that when an arc is maintained at the end of an electrode coated on half of its cylindrical surface only, the axis of the arc is not maintained in line with the axis of the electrode, but takes up a position away from the coating; it is easily conceivable, therefore, that with an electrode produced in the manner criticized the axis of the arc will be deflected away from the existing position of the overlapping yarn, and will rotate as the coating is removed. This phenomenon is referred to in Appendix III. In practice the electrode is seldom held normal to the surface of the work, and there is therefore a periodic distortion and a variation in the virtual length of the arc, which does not tend to give stability. This points to the importance of improving the present methods adopted for coating heavy slag-depositing rods. With reference to the physical conditions of the electrode in close proximity to the arc, it is obvious that, owing to the I^2R losses in the electrode itself and to heat conduction along the length of the electrode, the temperature of the wire itself must be increasing. In practice the value of the maximum current which can be used with any particular size of wire is limited, at least on electrodes of sizes below No. 5 S.W.G., by this temperature-rise. In general, for all types of electrodes and in particular for bare and thinly coated rods, more efficient work would be performed, and the rate of deposition increased, if the wire were tapered so as to reduce this temperature-rise. For instance, given a wire 16 in. long, tapered from end to end, say from No. 10 to No. 8 S.W.G., it will be possible to deposit this with a current of approximately the same value as is at present used with an ordinary untapered No. 8 rod. The tapered wire mentioned would be roughly equivalent to a No. 9 S.W.G. untapered rod, and it is obvious that the average current density will have been increased without the detrimental overheating of the electrode. I should like to draw the author's attention to this matter, as he may not be aware that a certain firm is at present carrying out investigations with a view to putting tapered wires of this description on the market, and his views on such a proposition would be of considerable interest. With regard to the ideal characteristics necessary in the welding circuit, it is important that the whole matter be reviewed from what is known of the arc performance under high, open-circuit voltage conditions. First, from the physical aspect of the subject of metal deposition by the arc, it appears that the conditions ideal for arc-stability are those giving constant watts in the arc within the limits fixed by the open-circuit voltage consistent with the safety of the operator, and excessive short-circuit current causing the electrode to "freeze" to the work. I suggest that, given a momentary condition in the arc when the vapour mass decreases in conductivity, it is necessary that energy be supplied to maintain the original rate of transference of metal across the arc, otherwise the trouble can easily be cumulative, resulting in the dying out of the arc. Another matter which appears to me to be of great importance in considering the stability of the arc is the ability of the apparatus or machine to counteract instantaneously sudden arc fluctuations. If it can be accepted that there are present in the arc conditions which give rise to high-frequency current fluctuations, I would suggest that the performance curves of various welding machines given in the paper are no guide to the actual ability of the plant to maintain a stable arc. The conditions set out above in regard to plant, electrode and operator call first for plant and electrodes which give a stable arc, and the broad characteristics of the machine are of secondary importance, as without stability the results of a non-stable arc wipe out all the beautiful points which might be claimed for first-class electrodes or welding plant. In conclusion, I should like to refer Messrs. Sayers to the reference made by the author to Mr. Holslag's paper given before the American Institute of Electrical Engineers on his welding transformer. I would suggest that in comparing their oscillograph records with those obtained by Mr. Holslag with his transformer, Messrs. Sayers will find the reason why the stability of their arc was so poor. If they replace their welding apparatus by one more suitable, and the electrode feeding mechanism by an average operator, I can assure them that they will get a more stable arc with bare wire.

Major J. Caldwell (*in reply*): It has been my endeavour in the paper to show that suitable apparatus, equipment and welding materials are now available for use. The conditions for using these to make good welds are known, and whilst these conditions include skill, experience and careful use of the apparatus, they are not more difficult to fulfil than those of many established industrial operations: it is at least not more difficult to train a reliable electric welding operator than a reliable welding smith.

I believe that the only possible means of permanently establishing electric welding as a standard method of construction is for the present manufacturers and designers of steel structures, with their special knowledge and experience as a guide, to indicate how electric arc welding, with its recognized advantages, can be applied to best advantage to secure satisfactory results at competitive cost.

The statement in the paper with regard to bare and flux-covered electrodes is a reflection of general opinion, but my own belief, based on experience with both methods, is that bare-wire welds are inferior in strength to those made with covered electrodes, and both Lloyd's and Admiralty specifications support this.

Mrs. Ayrton's views in regard to arcs must command respectful attention, and I am much gratified by her comments and suggestions. Perhaps the difference between my "contact resistance" and Mrs. Ayrton's "very thin layer of (carbon) vapour" to account for the constant term in the potential difference of an arc between electrodes of a given material, is not very great. If the electrode material is such that it remains in the state of vapour right across the arc—which seems to be the case with iron—contact resistance may better fit the facts. I would suggest that in any case this constant potential difference is connected with the energy absorbed in the vaporization of the material. Mrs. Ayrton doubts the real transfer of metal across the arc, but, in welding, the work gains weight and the electrode loses weight. Mrs. Ayrton agrees with the

views expressed in the paper, viz. that there is condensation of the vapour. The suggestion that welding is easier at high frequencies is borne out by some experiments at 200 periods per second, which showed that the manipulation of the arc is decidedly easier at that frequency than at 50 periods. Whether the weld is better remains to be proved.

Mr. Hobart's suggestion that British and American welders should probe to the bottom their difference in practice, i.e. the question of bare versus flux-coated electrodes, is excellent. It can only be done by research, as there are many variables involved in practical welding. Mr. Hobart has himself done much to stimulate arc welding research in the United States, and Dr. Sharp gives rise to a hope that he and Mr. Hobart may do something on the other side to initiate such combined research on this and other unsolved problems of arc welding.

Mr. Darling suggests that tensile tests of welds may be of value in deciding between bare and covered electrodes, but the example which he gives of the difference between welds made by the same welder, with the same electrode on the same plate, shows that tensile-test results have to be treated with caution. As the result of many tests, including tensile tests, both the Admiralty and Lloyd's specify flux-covered electrodes for strength welds. I agree with Mr. Darling that there is room for research into the chemistry of arc welding, and also that there is abundant evidence of definite projection of the iron across the arc. Visible drops of molten iron do fall from the electrode on to the work in horizontal welding, but they do not weld into the work properly, and are generally oxidized. They are more in evidence with bare than with flux-covered electrodes.

Captain Wallis-Jones's statements as to the costs of the resistance welding of thin material are very welcome. Spot and seam resistance welding are well established as valuable manufacturing processes, but there are occasions when arc welding on thin material is of value because the work is not accessible to a resistance welder or there is not enough of it to justify making a suitable machine. I have already sent to the Institution Library the two Reports mentioned by Captain Wallis-Jones, and I have to thank him for his generous remarks on my work at the Admiralty.

I am glad that Mr. McClelland has stated so clearly the advantage of flux-covered electrodes in providing a sheath of inert gas or liquid slag surrounding the molten or vaporous iron. As regards the relative merit of a.c. and d.c. welding, a good deal has been done since the date of the tests mentioned in determining the practical conditions for making a.c. welds, and my present opinion, as stated in the paper, is that intrinsically there is little or nothing to choose between the two methods. The striking of the a.c. arc is a little more troublesome until the knack is acquired. The voltage mentioned by Mr. McClelland for bare iron electrodes seems very much on the high side, if he means the voltage across the arc. In the automatic welder exhibited at Olympia by the B.T.H. Co. it was noteworthy that the voltmeter across the arc gave a very constant reading of only 15 to 18 volts. Undoubtedly the electrode material has an influence on the voltage-range consistent with sound welds.

Mr. Wedmore's offer of the assistance of the Electrical Research Association is noted with thanks, and it may possibly be accepted in the future.

Mr. Sayers's oscillograms show very clearly how the arc characteristic makes its own voltage curve, and the spectra described appear to prove the value in a.c. welding of a flux coating which provides conducting vapour of lower temperature than that of the iron, and therefore acts as a bridge across the current intermissions.

The reference to the vaporization heat of iron is to be found in a paper * by Mr. J. W. Richards, which gives the value of 1 110 calories per gramme for the latent heat of vaporization of iron, and the boiling point of iron as 2 698° (abs.). The latent heat value corresponds to 781 grammes evaporated per kilowatt-hour.

In reply to Mr. Baker, oscillograms of the d.c. welding arc current show variations much too rapid for either excitation or clutch regulation to follow. The inclusion of some reactance in the steadying resistance greatly reduces the amplitude of these rapid variations.

Mr. Flood quite rightly considers the successful arc welding of bronze and copper to be a very important development. In this branch, again; practice is ahead of theory, and I cannot at present supply more data. A number of samples of work accomplished were on view at the meeting, and can be seen by anyone sufficiently interested to communicate with me. Mr. Flood's views on the advantages of a.c. versus d.c. welding plant are quite sound, but, as the discussion shows, there is a considerable body of adverse opinion in respect to the relative quality of a.c. and d.c. welds.

Mr. Kennedy thinks that the electrode coating should fuse at a lower temperature than the iron. It should not be much lower, or the electrode will oxidize at the exposed tip. On the other hand, it should not be much higher, or the electrode will "cup" deeply, unless the covering disintegrates instead of fusing. This disintegration actually occurs with some flux compositions and is easily seen with the projection apparatus.

Mr. Ogden's discussion of the mechanism of the transfer of metal across the arc raises more points than I can deal with in this reply, but on the whole I think it favours the view that a difference of temperature between the electrode and the more massive work is a necessary and even the chief condition of the transfer. The electrostatic force is certainly one factor to be considered. I agree with him that the explosion of occluded gas is not the cause. The drops passing to the side of the arc as seen in the projection are certainly masses of molten flux.

Mr. Smout's suggestion in regard to the tapering of electrodes is new to me, and there would have to be clear proof of considerable advantage in working to justify the extra cost of manufacture. His criticism of the instability of the arc as shown by Messrs. Sayers can be met by the statement that the supply conditions at the Institution were not altogether favourable. In their own test-room it is quite usual for an entire electrode to be consumed without any interruption.

I feel that the members of this Institution are best

* *Transactions of the American Electrochemical Society*, 1908, vol. 13, p. 447.

qualified to assist in the development and to appreciate the considerable future of electric arc welding, not only as an addition to the load factor of power supply undertakings, but also as an outstanding example of the industrial usefulness of electricity.

The question of unemployment very materially affects members of the Institution, and I therefore welcome the reference made by Mr. Baker and Mr. McClelland to the training of electrical welders. Electric welding has been advocated for the following reasons:

(1) It effects repairs which would otherwise have been impossible.
(2) It provides water- and oil-tight jointures.
(3) It increases production in the manufacture and erection of steel structures, owing to the speed of working and the ease with which unskilled labour can be utilized to secure maximum strength.
(4) It settles labour disputes by providing another method of construction and repair.
(5) It provides employment for disabled Service men.

In addition to the training of welding operators at the Royal Dockyards, shipyards and engineering works by the Admiralty, facilities were provided towards the end of the war by the Ministry of Munitions at Loughborough, Birmingham, Acton and Bradford for the instruction of discharged soldiers to a limited extent. It was proposed to increase the capacity of these training centres and to incorporate a much larger scheme including Glasgow and Newcastle. I very much regret that this proposal was shelved on the cessation of hostilities and, as I cannot think of any craft at which proficiency can be secured so quickly, I submit that the matter should receive more consideration now by the Ministry of Labour, and for my part I would gladly hand them the information which was prepared for the purpose in 1918.

In conclusion I am pleased to acknowledge that the important points in the paper have all drawn information and criticism from qualified contributors, and I hope that the interest shown is indicative of speedy future progress in both the theory and practice of electric arc welding.

ADDRESS TO THE LONDON STUDENTS' SECTION.

By C. H. Wordingham, C.B.E., Past President.

(*Address delivered before the* London Students' Section, *10th November,* 1922.)

It gives me great pleasure once more to address you. Probably none of those present to-night have heard the addresses which I have given to this Section of the Institution on previous occasions, but I will, none the less, try to avoid repeating what I have previously said.

Most of those present are in the habit of listening to a large number of lectures on scientific and technical questions delivered by extremely able professors, and, instead of endeavouring to emulate them, I propose to speak rather of engineers than of engineering.

It is now some 35 years since I passed from the Student to the Associate Member class. As one gets older, and sees the younger men with their feet just set on the long ladder which one has traversed oneself, one is filled with sympathy for them and a longing to help them by pointing out the rotten rungs, the places where an alternative ladder presents itself, and the narrow plank in space that must sometimes be crossed.

Most often youth is impatient and resents any attempt at interference with its own judgment, but I must risk this possible hostility and do my best according to my lights.

One of the greatest temptations which besets those who study science is a tendency to cocksureness and a contempt for those who, in the earlier times in which they lived, were ignorant of present-day knowledge and achievement. The purely scientific man is prone to formulate theories, to test them at a few points, and then to speak of them as ascertained truths. The young student is impressed with what he takes for the triumph of intellect, and is intolerant of those who are somewhat sceptical of the new-found truths and who cling rather to what these old-fashioned people regarded as eternal verities, matters on which the young student is often ill-informed, and which he is apt to dismiss as contemptible trash which can have no place in his intellectual and scientific mind.

In successive years one sees examples of this attitude of mind in meetings of the British Association, that curious conglomeration of picnickers, some of whom are in the forefront of science, some ultra-scientific in a field of microscopic extent, and many of whom are of the gullible general public, open-mouthed to swallow any modern wonder at its face value, having barely a smattering of scientific knowledge. Year by year we are treated to elaborate speculations as to the origin of things, or are told that man with all his attributes is merely a cleverly made machine. Newspaper articles solemnly warn the churches that they must reconsider their position, as though the

speculations reported were ascertained facts. Next year some other learned pundit brings forward some other wonderful theory and the discredited one of the year before is forgotten; once more the newspaper takes up its cocksure attitude as to all old-fashioned ideas being exploded. One and all of the speculators, however, forget to explain where the actual origin came from and who designed the clever machine.

Another aspect of modern conceit is in respect of modern invention. I am second to none in my admiration of the cleverness, perseverance, and hard work devoted to the making and perfecting of modern inventions, but I do feel a very serious doubt as to whether mankind is really the better or the happier for many of them. The vast majority of modern inventions are devoted to speeding-up things; the bicycle enabled a man to move faster than he could by running; the motor easily outstripped the bicycle, and the flying-machine the motor. The result is that everyone by the use of these machines can do more in a given time than he could before their advent. Is he better in health or happier in mind for the facilities he possesses? Is it not a fact that the speeding-up of things has increased the number of nervous breakdowns, a disease unknown I suppose to our grandfathers, and has made the lives of many one long round of incessant, anxious work? The telegraph, the telephone, the railway, the ocean liner, all marvellous instances of human ingenuity, have the same tendency, and in addition they have taken much of interest out of the world by bringing all the more important towns to one dead level so that travel has lost most of its interest.

The much vaunted printing-press, while undoubtedly effecting an enormous amount of good, has of late years had much of this good discounted by rendering possible the daily and weekly newspapers (I do not refer to the technical journals) which consist chiefly of a mass of garbled statements, such statements having little relation to truth and being generally paid for by a political party or by people with axes to grind or things to sell. No sensible person will ever place the slightest reliance on anything which he reads in a newspaper published at the present day, without independent corroboration.

Probably, without exception, each one of my audience has by now classed me as a gloomy or foolish pessimist, as a reactionary idiot, or an old fossil in his dotage—I do not mind.

Admittedly I have given you only one side of the picture, and I further admit freely that I always travel by the fastest express trains and the fleetest motors, make every use of the telephone and telegraph, do everything electrically that I can, and as far as possible am in two places at once and get 25 hours into the day. All I want to impress upon you is that I do not believe I am any better in health or happier for it all, but I must do it because I live in the century which, as Carlyle would say, "flatters itself it is the twentieth."

I want to convince you, if I can, that all these inventions and discoveries are merely froth on the sea of life. They are here to-day and superseded to-morrow, and I believe that many of the achievements in ancient times, effected under civilizations of which there is now no trace or only traces of the slightest, were in fact more wonderful than our own.

I do not think that I can express better what I have in mind than by quoting a few lines of a poem by Campbell, with which some of you may be familiar, entitled "The Last Man." The poet is picturing the end of the world as seen through the eyes of the last survivor of the human race, and in addressing the sun he says:—

"What though beneath thee man put forth
His pomp, his pride, his skill,
And arts that made flood, fire and earth
The vassals of his will—
Yet mourn I not thy parted sway
Thou dim discrownéd king of day,
For all those trophied arts
And triumphs that beneath thee sprang,
Healed not a passion or a pang
Entailed on human hearts."

The things which really matter are the abstract qualities of man—not his machinery, but what we old-fashioned people call his soul and spirit, his love of truth, of justice, of honour, his capacity for love, sympathy, self-denial.

There is no denying that the world is in a very parlous state, and we are one and all suffering from it in one way or another, in greater or lesser degree. I believe that the main reason is that mankind has lost sight of the things that matter and has magnified material activities to such an extent that they have usurped the place of the vital essentials of life.

One important direction in which invention has been most prolific and successful is that of labour-saving appliances. Do not mistake me; under the conditions which we have created for ourselves to live in to-day, such appliances are absolutely essential. They have been invented, we must reckon with them and use them, otherwise we must go down in the fight. I believe, however, that, so far as the formation of human character and the promotion of human happiness are concerned, they are almost wholly bad. They have taken the interest out of life for most of the workers. It is true that each man can produce far more in quantity, and to a much greater degree of accuracy so far as dimensions are concerned, by making one small part of an article than by making the whole thing. But what is the price to be paid? An utter absence of any pride in his work, the elimination of all interest in it, with the result that instead of the craftsman's satisfaction in the designing and successful construction of some article of beauty or utility, there is a dull or sometimes fiery resentment at having to devote so many hours a day to repetition of certain motions of the limbs calling for little or no skill.

Another, and even greater, evil is the aggregation of these human automata in large numbers under an organization which is as dead and machine-like as the tools they operate. Just as no man can add a cubit to his stature, so no man, singly or in the mass, can change the nature of the human being which is not an automatic machine but an assemblage of passions

and sentiments of infinite variety of both kind and strength. We are suffering now acutely in industrial unrest resulting from this callous disregard of those laws of the universe which we may investigate but may not alter.

A man is endowed with faculties, powers which enable him to work, to contrive and to execute, and he is so constituted that he must have contact with others of his kind on which to exercise his human attributes. Only in proportion as he has the opportunity of exercising those faculties and powers will he be happy and healthy in mind and body. Deny him that exercise and he becomes a monster and the world a terrible place to live in.

Now, you will ask, what has all this to do with engineering, and, more especially, with the engineering student? I will tell you. Most of you are starting, or have just started, on your careers: what is necessary for your success? Naturally you must be equipped with the very best scientific and technical education you can obtain. Subject possibly to the exception of a few brilliant men with inborn genius who do arise from time to time, the day has gone by when the man who picked up his knowledge as he went along can hope to attain a good position as an engineer. Every young man entering the profession must make himself acquainted with the present state of knowledge in the various branches, and must have a special knowledge of the one in which he proposes to practise. This knowledge, however, as I have said elsewhere, is only his bag of tools. The finest kit in the world will not carry him far if he does not know how to use them. It is in the use of them that the human element comes in and that the exercise is called for of such abstract qualities as sympathy, kindliness, consideration, firmness, fairness and honour. These are the determining factors. The works manager who has favourites, who tries to get the better of his men, who bullies and insults those under him, or truckles to a dishonest employer by allowing scamped work, will never be a success. The adviser whose advice is coloured by his own self-interest, or who is open to bribery, may make money but he will never attain an honourable position. The staff man whose heart is in his amusements and who only does so much work as he is compelled, doing it as an uncongenial task to be put out of mind when he puts on his hat, will find his promotion slow and his change of employment frequent.

It is the man himself who counts. He must have his equipment of knowledge and skill, but also he must be able to use that equipment.

Just one word on the subject of work. The fashion of the day is to exalt amusement as the chief aim in life, and to represent work as a task to be reduced to the shortest period possible. So far have things gone that a man's opportunity to work is in certain directions forcibly limited by Act of Parliament. Work is essential to our existence, and it behoves each one of us to find out for himself what kind of work he is best suited to perform and then to find means to make it his vocation. Ordinarily, many drift into their life's work, but I imagine that few drift into engineering; most enter the profession from deliberate choice, presumably because it attracts them. Fortunate indeed are they if they have correctly gauged their inclination, for the true engineer needs no artificial amusement, his work is his hobby and is seldom out of his mind, even when taking, as he should, legitimate relaxation.

Most of us must have asked ourselves at one time or another: What is man's ultimate destiny? What are we here for? Each must find his own answer. I suggest that one of the most important objects in life is the formation of character, and if this be so, every thought, every action has its effect, indelible and permanent. Every job carried out assumes then an importance far greater than its intrinsic worth would give it. The primary thought in every engineer's mind should be: "Will this thing which I am carrying out be to my credit as an engineer or to my discredit? Suppose the work which I am doing to-day, and which will soon be out of sight, is unearthed 20 years hence, will its discoverer say of it that the job was well done or scamped?" I know of no pleasanter sensation than that of revisiting something carried out years ago and being able to tell oneself that it has stood the test of time and is still functioning well. I would say to each of you: "Try to do every piece of work primarily for the work's own sake and for the sake of its effect on your own character. The pecuniary reward in any one instance may be small or great, but in the long run that too will be added to you."

This country, perhaps more than many others, is suffering from a disregard of the principles which I have been trying, very lamely I fear, to enunciate. Work is in very bad odour just now. The doctrine that happiness is the be-all and end-all of existence is screamed at us from numerous quarters. Happiness is confounded with amusement, leisure and the possession of money, all of them hideous counterfeits of the real thing. A duty accomplished, a difficulty successfully overcome, a job well done, these are the things which confer real happiness, happiness worthy of man with his infinite possibilities and responsibilities.

Duty is a word seldom heard nowadays; "Rights" has taken its place. Read the letters written a century ago and you will find the word "duty" constantly in the mouths of our forefathers. Who built up our great Empire? The men whom England expected would do their duty, and who did it. Who are endangering that Empire? Those who preach pleasure, falsely so-called, as the greatest good, who honour a man according to the amount of money he possesses however he may have gotten it, and who call evil good and good evil.

Each of you young men has it in his power to work for his country, as so many of your number died for it only a few short years ago, and to help so to direct the course of events that this great nation of ours shall go up and not down in the scale of humanity and in its upward progress shall be an agent for the uplifting of mankind at large.

ADDRESS TO THE SCOTTISH STUDENTS' SECTION.

By J. F. Nielson, Member.

(*Address delivered before the* Scottish Students' Section, *17th November*, 1922.)

To all Students of this Institution I would emphasize the advantages of attendance at, and participation in the meetings of the Students' Sections. There is nothing more conducive to clear thinking than the writing of a paper. It need not be the account of original research work accomplished by the writer; indeed few of you will have an opportunity to present such a contribution. In this connection it is very gratifying and indeed encouraging to learn that one of the Students connected with this Section, Mr. J. C. Stewart, who contributed a paper last session on "Electricity in Mines," has been awarded by the Council a Student's Premium. It is to be hoped that at least one paper to be read before this Section during the present session may be similarly rewarded. Again, by joining in the discussions—and you need not fear to express your opinions or show an appetite for information on any subject for fear there may be a "chiel amang ye takin' notes," or if there is, "he'll no prent it"—an excellent training in self-assurance as to one's ability to give expression to one's ideas is obtained. Such a training will be found to be invaluable in years to come. Then again, at meetings such as these, opportunities occur, sometimes quite unexpectedly, of making the acquaintance of contemporaries, the consequences of which may be far-reaching in influencing your future and in moulding your careers. Do not, however, let these ideas, however admirable and desirable they may be, dominate your thoughts too exclusively. One of the finest definitions of a gentleman I have ever come across is: "he who puts more into life than he takes out of it." As members of this Institution you will have frequent opportunities of putting this virtue into practice—giving more than you get. As engineers you will, if you properly apprehend your calling, be assisting much more effectively than the politician in the creation and fostering of such an ideal atmosphere for human society as—to quote the words of Edmund Burke—is grounded in "a partnership in all science; a partnership in all art; a partnership in every virtue, and in all perfection." Such surely is the ideal towards which statecraft should be directed if the future peace of the world is to be maintained.

I am well aware that a proper apprehension of the calling of the engineer by those who practise it does not always exist, and that there are those who come into close contact with the forces of Nature without being affected thereby; still, I think, to most men such an experience must arouse feelings of the puniness of mankind and the boundless possibilities for discovery in still untrodden fields.

This year (1922) is memorable in the history of electrical engineering and of that particular branch of it to which our great citizen, Lord Kelvin, contributed so much of the fruits of his genius. I refer, of course, to the Jubilee of the founding of the Institution and of the Eastern and Associated Telegraph Companies.

The Institution was really founded earlier than the 28th February, 1872, but that was the date when its first Meeting was held. Electric telegraphy was then, as Dr. Kennelly says, mighty both by land and sea. Sir James Anderson, one of the pioneers of submarine telegraphy, presented a report to the Statistical Society in 1872, in which he stated that the total capital invested in submarine telegraph companies amounted to £10 230 370, and the total length of cables laid was 37 795 miles. These figures are very significant of the progress made by the telegraph industry since the first Atlantic cable was laid in 1858, only 14 years previously. It was even more striking to read a few months ago, when the Eastern and Associated Telegraph Companies were celebrating their Jubilee, that 28 000 miles of submarine cable had been laid since the Armistice. When wireless telegraphy and telephony are making enormous strides to-day and there seems no limit to the possibilities of its further development, such figures as these seem to show that telegraphy by wires is more than holding its own against its younger rival.

While, then, telegraphy was a sturdy child at the date of the inception of the Institution and it was because of its growing and sturdy condition that the Institution, or as it was first and not unnaturally called, the Society of Telegraph Engineers, came into being—electric lighting, electric traction, electric power transmission, electric telephony and a whole long list of other now familiar electrical activities were non-existent. Radio communication, as Dr. Kennelly remarks, was then undreamt of.

In this shipbuilding "hub of the universe" a few facts regarding the genesis and progress of electric lighting and power transmission on board ship may be of interest to you, especially to those who, like myself, are engaged in this particular branch of our profession. Illumination by arc lamps was the first method adopted on board ship. This was only natural, seeing that the invention of the arc lamp preceded that of the Swan or incandescent lamp by several years. Then, too, the series connection of lamps was the only method thought to be possible at first. Parallel running, or "subdivision of the current" as it was then called, was hardly considered practicable, and it was apparently not until about the year 1880 that attempts were made in that direction. In that year Edison in America installed on the steamship "Columbia" 115 10-c.p. incandescent lamps and, apparently about the same time, arc lamps were used for the internal illumination of the steamship "City

of Berlin." The following year (1881) saw, so far as I can learn, the first instance of incandescent electric lighting installed in a vessel built on the Clyde. This ship was the Cunard steamer "Servia," constructed by Messrs. G. and J. Thomson, Ltd., the founders of the Clydebank shipbuilding yard of to-day. This vessel had 117 Swan lamps and two arc lamps. The power required was about 10 kW and in all probability was furnished by a single-phase a.c. machine, driven by an endless cotton rope from a low-speed engine.

In this same year, incandescent electric lighting was introduced into the British Navy, the ship chosen being H.M.S. "Inflexible." Lord Fisher refers to the incident in the second volume of his memoirs and tells how it was owing to his interest in the Swan lamp and to Mr. Henry Edmund's lucid demonstration of it in a shed in Portsmouth Dockyard in the presence of the Admiral, surrounded by such a bevy of ladies as reminded Mr. Edmunds of his prototype in "H.M.S. Pinafore," with "his sisters and his cousins and his aunts," that the momentous decision was made to install this new illuminant in the "Inflexible," of which Fisher was then Captain.

Mr. James Lowson in his address to the Scottish Centre * mentioned the interesting fact that the first insulated wires used for ship lighting were covered with cotton cloth and white lead and that where they had to pass through specially damp places they were provided with additional protection of rubber tubing. Mr. J. H. Holmes, one of the pioneers of this branch of the industry, tells how they nearly set the "City of Rome" on fire after starting up the generating machinery. Seemingly they did not know much about fuses in those days and, to their consternation, sulphurous smoke was seen arising from the rubber-insulated wires in the music saloon. There being no switches nearer to hand than the engine room, a rush was made for it, the fire was extinguished and the painters bribed to work all night and cover up all traces of the mishap. Mr. Holmes's remarks about the absence of switches recalls to my mind a report made by one of my friends on the trials of the generating plant fitted on board the s.s. "Friesland," a steamer built in 1889, which it is interesting to find was, even at that early date, fitted with a Parsons turbo-generator.

He says: "One turbo-generator alone carried the full load of lights without the slightest hitch. The main cable was drawn out of its binding post repeatedly, thus throwing off the full load of 450 lamps, but the engine adjusted its speed instantaneously without the stop valve being touched at all." He says nothing about the replacing of the cable into its binding post. Presumably that also was done with the generator running, altogether rather a difficult business.

As you are all probably aware, the earliest form of incandescent lamp manufactured in this country was the carbon-filament type, invented by Sir Joseph Swan, I think, in the year 1878. They were far from being a satisfactory article at first, as they were made from parchmentized cotton and were very fragile. Breakages were numerous and, as the price was 35s. per lamp, experimenting with them was a decidedly costly affair.

* *Journal I.E.E.*, 1915, vol. 53, p. 37.

Glasgow has, we are told, the distinction of being the first town in this country in which this new form of illuminant, the Swan carbon-filament lamp, was publicly exhibited. The outcome of this exhibition was that Colonel Crompton got orders to install these lamps in the Glasgow Post Office and the goods yard of Queen-street station. The next step in lamp manufacture was the Nernst lamp, followed by the tantalum filament. From that we have come to the tungsten lamp and, last and perhaps the greatest jump in improvement of all, the gasfilled lamp. How tremendously we have progressed in the making of incandescent lamps since those pioneering days 40 years ago can only be fully appreciated after walking through a modern lamp factory and witnessing the hundred-and-one processes, some performed by hand labour and others by the most ingenious of automatic machinery, through which the vacuum and gasfilled lamps have to pass before they reach the final stage in their manufacture.

Reverting again for a few moments to the progress made in the application of electrical science to the navigation and internal economy of the modern steamship since those days, 40 years ago, when the electric lamp began to displace the evil-smelling and dangerous oil lamp, it is only natural that we should find electricity being first used as a transmitter of power for driving fans to improve the ventilation of the lower decks. Since then it has found ever-increasing application on board ship until practically every piece of rotating machinery outside of the engine room, and much of the auxiliary machinery within it as well, is now driven electrically. For every purpose requiring the transmission of orders, messages, records of movements of gearing of all kinds, temperature indications, the rejuvenation of the human frame by artificial solar heat and the still more artificial hobby horse, the ozonizing of vitiated atmosphere and many other purposes too numerous to mention here, electricity is becoming more and more indispensable in the modern passenger liner. Last winter one of your members gave an exhaustive description of the gyroscopic compass, an instrument which was made possible by the application of electric power, and which is threatening to displace the magnetic compass in our large liners, owing to its many advantages over its older rival.

Electricity has also made possible another application of the gyro wheel. I refer to what is known as the Sperry "stabilizer," by means of which it is possible to reduce the rolling of a vessel even in the worst of weather. Apart from the obvious comfort which such a device must bring to the average passenger who is prone to suffer from *mal de mer*, it has the less obvious commercial advantage of appreciably reducing the power required to propel a vessel in heavy weather and of greatly minimizing the shipping of seas by keeping it on an almost even keel. Of course I should mention that these applications of the gyroscope to the navigation of ships are costly, more particularly the stabilizer, and can be considered only where the shortening of the voyage by maintaining a straighter course and the saving in propulsive effort more than counterbalance the capital outlay.

The advantages of electric heating and cooking are

beginning to be more and more appreciated on board ship and already we find the coal-fired cooking range being displaced by an electrically heated one on some of our cross-channel steamers. This is not surprising, for the benefits to be derived from electric cooking, which are so self-evident in the domestic kitchen, are even more apparent in the galleys of such vessels. The cleanliness, comfort and absence of waste heat require to be seen and experienced to be fully appreciated by those accustomed only to the older methods and discomforts of coal-fired ranges.

The advent of the Diesel motor ship has given a fresh fillip to the electrical industry. A cargo steamer of possibly 10 000 tons' carrying capacity, which, if propelled by reciprocating steam engines or geared turbines, might have a small electric lighting plant of about 25 kW, will probably now have generators of a total capacity of 400 to 500 kW, the absence of steam boilers necessitating the whole of the deck machinery, including steering gear, capstans and windlasses and, in the engine room, large air compressors and all the pumping plant, ventilating fans and refrigerating machinery, being electrically driven.

From this point I might proceed to describe the position in which we stand to-day as regards electric propulsion of ships and some of the later uses to which electricity has been applied in their construction. I feel, however, that I could not do justice to such a theme in a few passing remarks and I propose, therefore, to turn instead to one or two topics which it seems to me are peculiarly of interest to Students of the Institution.

The first thing I should like to say to you is that it is far harder to rise in your profession to-day than it was in the early days of the industry. It was then, in comparison with to-day, relatively easy to rise above one's fellows and to become, shall I say, a giant among pygmies. Forty years ago the biggest intellects in the world were engaged in developing existing industries. The average electrician of those days was but a dabbler in science and an amateur in invention. Consequently it was comparatively easy to rise in the industry and to maintain one's reputation in the face of a gradually growing influx of younger trained men. To-day we have a very large number of highly trained scientific and business men engaged in the electrical profession. The problems which were then difficult and seemingly impossible of solution are now quite elementary and easily understood. The problems which remain to be solved are of a very much more abstruse character and are being tackled by many who have benefited by the discoveries of those early pioneers and whose equipment for such research work is infinitely superior to their predecessors'. It is for such reasons as this that I say that it is exceedingly difficult to-day for any but the most brilliant genius to rise much above the level of his competitors. I am not saying these things to discourage you but in order that you should appreciate how much greater is the necessity for continuous effort if you are to attain to eminence in your profession to-day.

Now, while it is not given to every one of you to rise in his profession much above the average level and thus to make your influence felt in the world, each may leave his mark upon his work in a manner which may be even more enduring than if he succeeded for a time in soaring above his fellows in public estimation. Every piece of work undertaken bears the impress of the worker, and the character of that impress depends upon the thoroughness with which it has been done and the spirit which has animated the doer. In the long run, the money-getting value of any piece of work is of the least importance. Of far greater value to the engineer and that which will advance him in the estimation of his fellow-men is the manner in which he has carried out his contract. Of course, every engineering problem involves questions of cost, and the successful engineer is he who employs the least capital in a job which in its working gives the greatest return on that capital outlay. This leads me on to say how very important it is that you young engineers should not lose sight of the commercial side of your professional training. Too little attention, I fear, has in the past been paid to this subject and, in consequence, many a student completes his college course or apprenticeship without realizing that the most important question that thereafter will confront him is the cost of the scheme which he is called upon to work out or the machine which he has to create.

It is not unnatural for the young engineer to lose sight of this fact. If he is at all keen on his work, what is more natural than that he should strive after perfection, but, in this imperfect world, perfection is a costly virtue and a luxury which can rarely be afforded. Then, too, the experience through which he has recently come during the years of war, when it was a case of getting everything done regardless of cost, has not helped to bring this fact home to him.

Some, if not indeed many, of you will have occasion to draw up specifications of work to be done. Here you have a subject of the very greatest importance to which I doubt if very much attention is paid in the training of the young engineer. Unless you are an expert in the manufacture of the machinery the performance of which you are specifying, and not even then, should you make the mistake of describing in detail how that machinery should be designed. That is not the object of a specification and, as I shall proceed to show you by one or two concrete examples, such a mistaken view of the nature of a specification often leads to waste of your own or your client's capital, with no counterbalancing advantage to you or to him. The main object of a specification is to state the duty which the machine or installation is intended to perform, the conditions under which it will operate, and the tests which will be applied in order to ascertain whether the performance is satisfactory. It is most essential if the cheapest, and at the same time the best, results are to be obtained, that the manufacturer or contractor should not be hidebound by stringent clauses in the specification, detailing how the desired results should be obtained. In such matters he should be left with the utmost freedom to adopt such methods of construction as he considers will reasonably fulfil the prescribed conditions. Of course the purchaser may have had previous experience with different kinds and qualities of material or methods of construction, and if such

experience leads him to object to the employment of certain materials or methods of construction, he may quite properly specify that if such materials are utilized, they shall fulfil certain conditions as regards, for instance, their tensile strength and that certain methods of construction shall not be employed. It is then open to the manufacturer to offer such other materials or methods of construction as he can guarantee from his experience are best suited to the machinery manufactured by him. It is, for instance, much more important that the manufacturer should be informed that the machine sought for shall be capable of being operated in, say, an engine room having a temperature of 120° F. and in a damp tropical climate, than that the coils shall consist of copper wire having a conductivity not less than 98 per cent of Matthiessen's standard; also that the current density in the conductors shall not be more than 1 500 amperes per square inch in the armature coils and 2 000 amperes in the field coils, and so on. It is surely only common sense to expect that the manufacturer will, for his own protection, use copper of the highest conductivity, properly annealed, and designers of electrical machinery will tell you that the current density at which the windings may safely be run depends very largely upon the cooling conditions. In some cases, such as shunt coils, it may not be found practicable to go beyond 800 amperes per square inch, while in the construction of the armature, the ventilating and heat-radiating surfaces may allow of a density far above 1 500 amperes per square inch being employed with impunity and still meet the temperature, i.e. the essential, clause of the specification.

I have quite recently come across instances, in private and Government practice, where, owing to just such causes as I have mentioned, some too obviously the result of slavishly copying out-of-date specifications, others of seemingly ignorant attempts to improve upon sound practice by piling safeguards upon safeguards already existing, hundreds of pounds have, or will be, needlessly thrown away and presumably by well-intentioned individuals who unfortunately act for clients who are unaware of these facts. And so I would close this topic by again impressing upon all young engineers the fact that the object of a specification is mainly to ensure the attainment of results and not to teach the manufacturer his business. Inform him as to what your plant is to accomplish, tell him the conditions under which it will have to work, and, having placed your contract in the hands of a firm of repute, it will be sufficient for you to see that they meet their guarantees.

It would be foolish to attempt to foretell the future, even its immediate prospects, for it must be very humiliating at this time to those who told us less than three years ago that the conditions then existing would probably continue for many years to come and that in consequence the prospect of employment for educated and trained electrical engineers was very promising. The situation, I need hardly tell you, is far from rosy, and as regards unemployment and the immediate prospects of employment for the younger men, especially in the engineering professions, things could hardly be worse than they are just now, but history has in the past repeated itself and will surely repeat itself again. The lean and anxious times we are passing through will assuredly pass away sooner or later—I venture to think that we have seen the worst already—and while we must not expect, nor should we expect, the industrial world of the future to work under conditions precisely similar to those prevailing before the war, I feel certain that there will be ever-increasing opportunities for those of you who are preparing yourselves to take advantage of them.

There are many new fields for the use of electricity which we have only begun to develop in this country. The Chairman of our Scottish Centre, Mr. A. S. Hampton, in his address told us of what has been done and of what remains to be done in the electrification of railways. Dr. Magnus Maclean has opened our eyes to the potentialities of water power in the Highlands; while Mr. Borlase Matthews told us recently of the beginnings of, and prospects for, electro-farming or the application of electricity to agriculture which, when we think of it, is still the greatest and the most essential industry in the world. The electrical propulsion of ships has only just made a beginning—I shall not venture to prophesy or express an opinion as to its future development. Radio-telephony may, if properly handled and developed, bring about profound changes in our domestic and economic life.

The Institution exists to promote and encourage every new endeavour and every new development in electrical science, and it is worthily fulfilling these functions. I would, however, have you remember that the future lies in your hands. Some of you will doubtless become Members of Council, and those of you who do not, will at least be able to criticize those who do. Some of you may be inclined to criticize the Council already, and such criticism is to be welcomed if the critic has the welfare of the Institution genuinely at heart. When you criticize do not, however, forget that the responsibility of office carries with it the cares of office, and that, while all things may be lawful, all things may not be expedient. The Council are trustees for its 10 000 members and, as such, must not be expected to launch into speculative ventures which may turn out disastrously for the health of the Institution. In closing, let me say that by doing what within you lies to promote the welfare of this Students' Section, you will be helping the Institution to attain to an even greater reputation than it holds to-day.

THE OPERATION OF INDUCTION MOTORS IN CASCADE.

By H. COTTON, M.B.E., M.Sc., Associate Member.

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The circle diagram of two induction motors in cascade can be drawn by elaborating the diagram for one machine functioning under normal conditions.

Let F_1 = useful primary flux, i.e. the primary flux which links with the secondary winding.
f_1 = primary leakage flux.

Then $(F_1 + f_1)$ = total primary flux = ϕ_1, say, and $\phi_1 = \lambda_1 F_1$, where λ_1 is the primary leakage factor.

Let F_2 = useful secondary flux, i.e. the secondary flux which links with the primary winding.
f_2 = secondary leakage flux.

Then $(F_2 + f_2)$ = total secondary flux = ϕ_2, say, and $\phi_2 = \lambda_2 F_2$, where λ_2 is the secondary leakage factor. Hence the resultant primary flux is the vector sum of ϕ_1 and F_2, and the resultant secondary flux is the vector sum of ϕ_2 and F_1. Remembering that the resultant secondary flux is in quadrature with the total flux produced by the secondary winding alone, i.e. with ϕ_2, we can draw the diagram for a single motor as follows:—

Draw Oa (Fig. 1) to represent F_1, and on Oa as diameter describe a semicircle.

From a draw a chord aC to represent ϕ_2 $(= F_2 + f_2)$. Join OC and draw OB parallel to aC, making OB = aC = ϕ_2. Then, since angle COB is a right angle, and since OC is the resultant of Oa and OB,

OC = resultant secondary flux.

Produce Oa to A, making OA = $F_1 + f_1 = \phi_1$. Mark off Ob = F_2. Then OD the vector sum of ϕ_1 and F_2 is the resultant primary flux.

In the case of a motor functioning alone, the line OD is the fixed line on the diagram, and its length is proportional to the magnetizing current. OA is proportional to the primary current on load, and the locus of A is a semicircle with its centre on OD produced.†

In order to derive the circle diagram of the cascade motor the following considerations have to be taken into account:—

First, the second motor being connected to the first motor receives its supply from this. The first motor is therefore functioning as a generator relative to the second. Also, in the case considered it is the rotor of the second machine which is the primary of that machine, and the stator which is acting as its short-circuited secondary. This latter condition is not, however, essential, as the stator of the auxiliary machine can be connected to the rotor of the main machine if the windings are designed with this end in view. The rotor-to-rotor method is treated here because it is suitable for two identical machines and therefore considerably simplifies the problem.

Secondly, because the rotor of the auxiliary machine is motoring on a current taken from the main rotor it will produce a back E.M.F. In order to simplify the diagram the case considered is that of ideal motors in which the copper losses are so small that they can be neglected. This means that the generated E.M.F. in the main rotor and the back E.M.F. in the auxiliary rotor will be equal and opposite. But the directions of rotation of the two rotors are the same, the shafts being mechanically coupled, hence the fluxes which

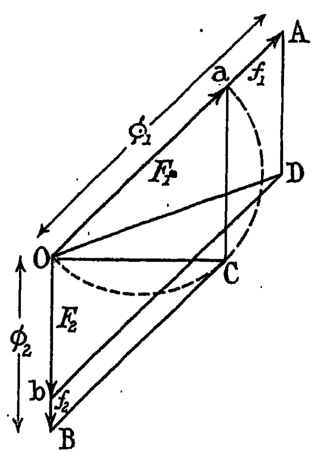

FIG. 1.

produce these E.M.F.'s must be in phase with one another when drawn on the same diagram. Also, assuming identical windings on the two rotors, the two fluxes must be equal in magnitude. The flux diagram of the auxiliary machine is drawn first.

Let ${}_1F_1$ = useful primary flux of machine 1.
${}_1F_2$ = useful secondary flux of machine 1.
${}_2F_1$ = useful primary flux of machine 2.
${}_2F_2$ = useful secondary flux of machine 2.

And so on, the prefix referring to the number of the machine, and the suffix to the winding, e.g. whether primary or secondary.

Mark off Oa = ${}_2F_1$ the useful primary flux (Fig. 2), and make OA = $\lambda_{2\,2}F_1 = {}_2\phi_1$, the leakage factor λ_2 being used because the rotor is functioning as the primary and the stator as secondary.

On Oa as diameter describe a semicircle and mark off

* This paper, which was submitted by the author as a thesis, was accepted by the Examinations Committee in lieu of the Associate Membership Examination.

† See BEHREND: "The Induction Motor."

the chord aC equal to the total secondary flux $_2\phi_2$. Then the resultant OC = the resultant secondary (stator) flux. Also making Ob = OB/λ_1 we have for the resultant of OA and Ob, OD = the resultant primary (rotor) flux.

Consider now the main motor. Since its rotor must have induced in it an E.M.F. equal and opposite to that in the second rotor, the resultant flux linking with it must be equal to the resultant flux of the second rotor, namely, to OD. One of the components of this resultant flux is the total flux produced by the rotor winding the whole set. Hence the locus of G is the required current diagram. The fixed line on the diagram is given by the vector OK representing the resultant primary flux. This line is constant in magnitude and direction, and is analogous to the fixed line OD in the circle diagram for a single motor. OK gives, when measured on the current scale, the magnetizing current of the set. Fig. 3 shows the completed diagram.

The locus of G is determined analytically as follows :—
Take the direction of OC as the x' axis, and the perpen-

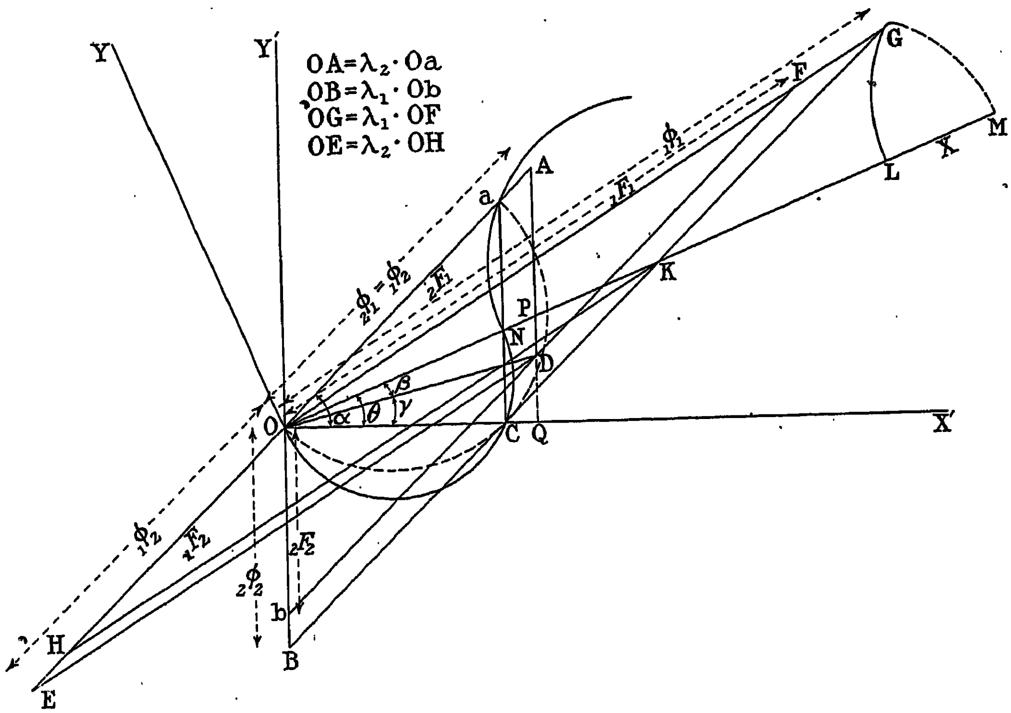

FIG. 2.—Construction of the circle diagram.

itself, that is OA = $_1\phi_2$ in the diagram, since the total rotor flux is the same in each machine. But since the rotor currents must be equal and opposite, the total rotor flux of machine 1, namely, $_1\phi_2$, must be opposite in phase to the vector OA and therefore represented on the diagram by OE, where OE = OA.

The other component of the resultant rotor flux is the useful stator flux $_1F_1$.

Producing OF to G and making OG equal to λ_1OF we have OG = $_1\phi_1 = \lambda_1 \cdot {_1F_1}$, the total primary (stator) flux of the main machine. Finally, since the resultant stator flux is the vector sum of the total stator flux $_1\phi_1$ and the useful rotor flux $_1F_2$, we can find this resultant flux as follows :—

OE represents the total rotor flux $_1\phi_2$. Hence, if we mark off OH equal to OE/λ_2, we have OH = $_1F_2$.

Completing the parallelogram OHKG gives OK the resultant primary flux. This completes the flux diagram.

Since the currents are proportional to the fluxes which they set up, the flux diagram is also, to a certain scale, a current diagram. Hence the vector OG, which represents the total flux set up by the current in the primary motor, also represents the current intake of dicular through O as the y' axis. Then the co-ordinates of the various points on the diagram are as follows :—

x' co-ordinate of C = $_2F_1 \cos\alpha$: y' co-ordinate = 0

x' co-ordinate of a = $_2F_1 \cos\alpha$: y' co-ordinate $= {_2F_1}\sin\alpha = {_2\phi_2} = \lambda_1 \cdot {_2F_2}$

x' co-ordinate of $A = \lambda_2\, {_2F_1}\cos\alpha$: y' co-ordinate $= \lambda_2\, {_2F_1}\sin\alpha = \lambda_1\lambda_2 \cdot {_2F_2}$

OD is the resultant of OA and Ob. Hence

x' co-ordinate of D = $\lambda_2 \cdot {_2F_1}\cos\alpha$: y' co-ordinate $= \lambda_1\lambda_2 \cdot {_2F_2} - {_2F_2}$

OF is the resultant of OA and OD. Therefore

x' co-ordinate of F = $2\lambda_2 \cdot {_2F_1}\cos\alpha$: y' co-ordinate $= 2\lambda_1\lambda_2 \cdot {_2F_2} - {_2F_2}$

OG is λ_1 times OF, hence its x' and y' co-ordinates are λ_1 times the corresponding co-ordinates of OF. Therefore

x' co-ordinate of $G = 2\lambda_1\lambda_2 \cdot {_2F_1}\cos\alpha$: y' co-ordinate of $G = \lambda_1 \cdot {_2F_2}(2\lambda_1\lambda_2 - 1)$

Finally, GK is equal and parallel to OH $= {}_1F_2 = {}_2F_1$ reversed. Therefore

$$\begin{aligned} x' \text{ co-ordinate of } K &= 2\lambda_1\lambda_2 \cdot {}_2F_1 \cos\alpha - {}_2F_1 \cos\alpha \\ &= {}_2F_1 \cos\alpha(2\lambda_1\lambda_2 - 1) \\ y' \text{ co-ordinate of } K &= \lambda_1\, {}_2F_2(2\lambda_1\lambda_2 - 1) - {}_2F_1 \sin\alpha \\ &= \lambda_1\, {}_2F_2(2\lambda_1\lambda_2 - 1) - \lambda_1\, {}_2F_2 \\ &= 2\lambda_1\, {}_2F_2(\lambda_1\lambda_2 - 1) \end{aligned}$$

Now since the only fixed direction on the diagram is the direction of OK, it is desirable to use OK as the x axis, and the perpendicular through O as the y axis. The new axes are therefore displaced by an angle KOC ($= \theta$, say) from the old axes in a counter-clockwise direction. Hence the equations for transformation are:

$$\left.\begin{aligned} x &= x' \cos\theta + y' \sin\theta \\ y &= y' \cos\theta - x' \sin\theta \end{aligned}\right\}$$

The co-ordinates of G with respect to the new axes are:

$$\begin{aligned} x &= d + \text{GK} \cos(\alpha - \theta) \\ &= d + {}_2F_1 \cos(\alpha - \theta) \\ y &= \text{GK} \sin(\alpha - \theta) \\ &= {}_2F_1 \sin(\alpha - \theta) \end{aligned}$$

Again, from Equations (1) and (2) we can determine the relationship between ${}_2F_1$, ${}_2F_2$ and d; for from Equation (2) we have

$$ {}_2F_2 = \frac{{}_2F_1 \cos\alpha \sin\theta(2\lambda_1\lambda_2 - 1)}{2\lambda_1 \cos\theta(\lambda_1\lambda_2 - 1)}$$

Substituting this value in Equation (1) we have

$$ {}_2F_1 \cos\alpha \sin\theta\,(2\lambda_1\lambda_2 - 1) + \frac{2\lambda_1 \sin\theta(\lambda_1\lambda_2 - 1) \times {}_2F_1 \cos\alpha \sin\alpha(2\lambda_1\lambda_2 - 1)}{2\lambda_1 \cos\theta(\lambda_1\lambda_2 - 1)} = d$$

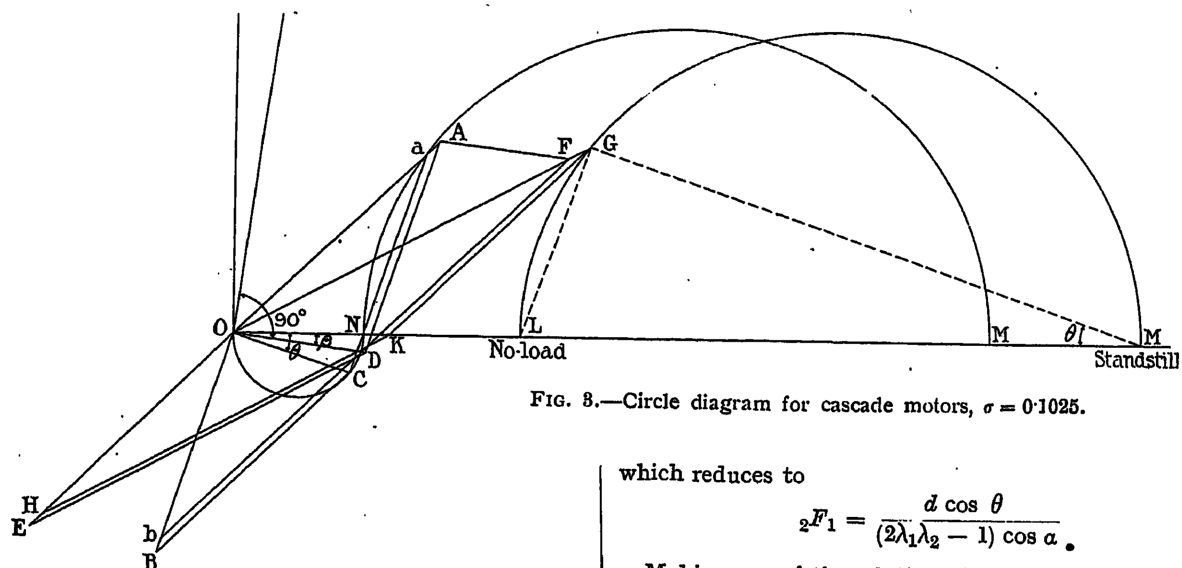

FIG. 8.—Circle diagram for cascade motors, $\sigma = 0{\cdot}1025$.

Hence for the co-ordinates of K (a fixed point) with respect to the new axes we have:

The x co-ordinate

$$ {}_2F_1 \cos\alpha \cos\theta(2\lambda_1\lambda_2 - 1) + 2\lambda_1 \cdot {}_2F_2 \sin\theta(\lambda_1\lambda_2 - 1) = d, \text{ say} \quad . \quad (1)$$

The y co-ordinate

$$ - {}_2F_1 \cos\alpha \sin\theta(2\lambda_1\lambda_2 - 1) + 2\lambda_1 \cdot {}_2F_2 \cos\theta(\lambda_1\lambda_2 - 1) = 0 \quad . \quad (2)$$

From Equation (2) we can deduce a relationship between α and θ, for we have

$$ {}_2F_1 \cos\alpha \sin\theta\,(2\lambda_1\lambda_2 - 1) = 2\lambda_1 \cdot {}_2F_2 \cos\theta\,(\lambda_1\lambda_2 - 1)$$

Again, $\lambda_1 \cdot {}_2F_2 = {}_2\phi_2$
$= {}_2F_1 \sin\alpha$

Hence substituting in the above equation we have

$$\cos\alpha \sin\theta\,(2\lambda_1\lambda_2 - 1) = 2 \sin\alpha \cos\theta\,(\lambda_1\lambda_2 - 1) \quad . \quad (3)$$

which reduces to

$$ {}_2F_1 = \frac{d \cos\theta}{(2\lambda_1\lambda_2 - 1)\cos\alpha}.$$

Making use of the relationship between ${}_2F_1$ and ${}_2F_2$ we have

$$ {}_2F_2 = \frac{d \sin\theta}{2\lambda_1(\lambda_1\lambda_2 - 1)}$$

Hence the y co-ordinate of G becomes

$$\begin{aligned} y &= {}_2F_1(\sin\alpha \cos\theta - \cos\alpha \sin\theta) \\ &= {}_2F_1\left\{\sin\alpha \cos\theta - \frac{\sin\alpha \cos\theta \times 2(\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2 - 1}\right\} \end{aligned}$$

from Equation (3)

Again,
$$ {}_2F_1 = \frac{\lambda_1\, {}_2F_2}{\sin\alpha} = \frac{d \sin\theta}{2(\lambda_1\lambda_2 - 1)\sin\alpha}$$

Hence the expression for y reduces to

$$ y = \frac{d \sin\theta \cos\theta}{2(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \quad . \quad . \quad . \quad (4)$$

In order to simplify calculation, transfer the origin

temporarily to K. Then the new x co-ordinate of point G becomes

$$x = {}_2F_1 \cos(\alpha - \theta)$$
$$= \frac{d \sin\theta}{2(\lambda_1\lambda_2 - 1)\sin\alpha} \times \left\{\cos\alpha\cos\theta + \sin\alpha\sin\theta\right\}$$

Substituting

$$\cos\alpha\sin\theta = \frac{\cos\theta\sin\alpha \times 2(\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2 - 1}$$

we have

$$x = \frac{d}{2(\lambda_1\lambda_2 - 1)\sin\alpha} \times \left\{\frac{\cos^2\theta\sin\alpha \times 2(\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2 - 1} + \sin\alpha\sin^2\theta\right\}$$
$$= \frac{d}{2(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \times \left\{2\lambda_1\lambda_2 - 1 - \cos^2\theta\right\} \quad (5)$$

In order to find an equation connecting x and y we have to eliminate the functions of θ. Expressing in terms of 2θ we have

$$y = \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\sin 2\theta$$
$$x = \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\left\{4\lambda_1\lambda_2 - 2 - (1 + \cos 2\theta)\right\}$$
$$= \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}(4\lambda_1\lambda_2 - \cos 2\theta - 3)$$

Put $\dfrac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} = P$

Then $y = P\sin 2\theta$
$x = P(4\lambda_1\lambda_2 - 3 - \cos 2\theta)$

Put $(4\lambda_1\lambda_2 - 3) = Q$

Therefore $x = P(Q - \cos 2\theta)$

Hence squaring and adding we have

$$x^2 + y^2 - P^2(Q^2 - 2Q\cos 2\theta) = P^2$$

Again, $-\cos 2\theta = \left(\dfrac{x}{P} - Q\right)$

Therefore $x^2 + y^2 - P^2\left(Q^2 + \dfrac{2Qx}{P} - 2Q^2\right) = P^2$

Therefore $y^2 + (x - PQ)^2 = P^2$

Re-substituting for P and Q we have

$$y^2 + \left\{x - \frac{4(\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\right\}^2 = \left\{\frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\right\}^2$$

This is the equation to a circle of radius

$$c = \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$

with its centre on the x axis situated at a distance

$$a = \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \text{ from K}$$

It is usual to express the quantities c and a in terms of the "dispersion coefficient" of the motor. This is sometimes taken as

$$\sigma = \lambda_1\lambda_2 - 1 \text{ and sometimes as } \sigma = 1 - \frac{1}{\lambda_1\lambda_2}$$

Taking the first as the more commonly used value we have

$$\lambda_1\lambda_2 = \sigma + 1$$

Hence the radius $c = \dfrac{d}{4\sigma(2\sigma + 1)}$

Retaining K as the origin, the points L and M, where the circle cuts the x axis, are given by the condition $y = 0$. Therefore

$$x - \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} = \pm\frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$
$$x = \frac{d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\left\{4\lambda_1\lambda_2 - 3 \pm 1\right\}$$
$$= \frac{d(4\lambda_1\lambda_2 - 2)}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \text{ or } \frac{d(4\lambda_1\lambda_2 - 4)}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$

This gives
$$\text{KL} = \frac{d \times 4\sigma}{4\sigma(2\sigma + 1)} = \frac{d}{2\sigma + 1}$$
$$\text{KM} = \frac{d(4\sigma + 2)}{4\sigma(2\sigma + 1)}$$

Now the distances of points on the circle from the original origin O are proportional to the fluxes or to the currents. Thus the length OL measured on the current scale gives the no-load current, that is the magnetizing current of the set. The length OM gives the standstill current.

We have
$$\text{OM} = d + \frac{d(4\sigma + 2)}{4\sigma(2\sigma + 1)} = \frac{d(8\sigma^2 + 8\sigma + 2)}{4\sigma(2\sigma + 1)} = \frac{d(4\sigma + 2)}{4\sigma}$$
$$\text{OL} = d + \frac{d}{2\sigma + 1} = \frac{d(2\sigma + 2)}{2\sigma + 1}$$

If we draw on the same diagram the circle for a single motor working alone, we can obtain a comparison between the two cases. The vector OG gives the total stator flux and OH the total rotor flux of the first machine. The resultant stator flux is OK, and therefore when measured on the stator current scale this length gives the no-load (magnetizing) current of one motor working alone. The phase will not be the same as that of OK, but this does not affect the numerical relationships between torque, power factor, etc., in the two cases.

Hence $\dfrac{\text{No-load current of combination}}{\text{No-load current of a single motor}} = \dfrac{OL}{OK}$

$$= \frac{d(2\sigma + 2)}{2\sigma + 1} \div d$$

$$= \frac{2\sigma + 2}{2\sigma + 1}$$

Now $\sigma = \lambda_1 \lambda_2 - 1$

and therefore, since the leakage coefficients λ_1 and λ_2 have in practice to be very nearly equal to unity in

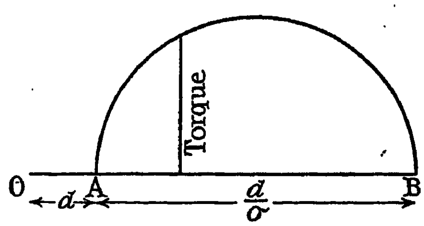

FIG. 4.

order to keep the power factor as high as possible, the numerical value of σ is very small when compared with unity. Hence the ratio of the magnetizing currents is very approximately two to one. This is to be expected since all the power received by the auxiliary motor has to come through the main motor, and the magnetizing current of the former is therefore superposed on that of the latter.

Again, for a single motor the ratio of the no-load current OA to the diameter of the circle AB is equal to the dispersion coefficient σ (Fig. 4). Hence the diameter of circle for a single motor $= \frac{d}{\sigma}$. But the torque of the motor is proportional to the perpendicular dropped from the working point to the x axis. Hence

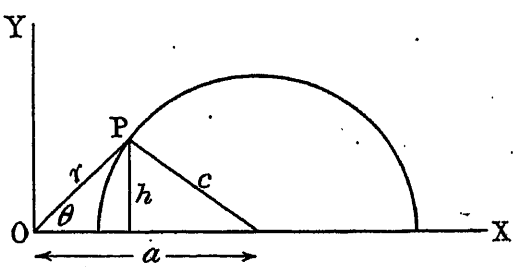

FIG. 5.

the maximum torque is proportional to the radius. Hence we have

Maximum torque of main cascade motor is proportional to c, that is to $\dfrac{d}{4\sigma(2\sigma + 1)}$.

Maximum torque for a single motor working alone is proportional to $\dfrac{d}{2\sigma}$.

Hence

$$\frac{\text{Maximum torque of main cascade motor}}{\text{Maximum torque of single motor}} = \frac{1}{2(2\sigma + 1)}$$

$$= \tfrac{1}{2} \text{ (very nearly).}$$

The power factor (P.F.) for any working point P is given by the cosine of the angle POY, that is by the sine of the angle θ in Fig. 5 (θ now having a different meaning).

Therefore $\quad \text{P.F.} = \dfrac{y}{\sqrt{(x^2 + y^2)}}$

But
$$y^2 + (x - a)^2 = c^2$$
$$y^2 + x^2 - 2ax + a^2 = c^2$$
$$x^2 + y^2 = c^2 + 2ax - a^2$$

and
$$y = \sqrt{[(c^2 - (x - a)^2]}$$

Hence $\quad \text{P.F.} = \sqrt{\left[\dfrac{c^2 - (x - a)^2}{c^2 + 2ax - a^2}\right]} = k$, say.

Differentiating with respect to x we have

$$\frac{dk}{dx} = \tfrac{1}{2}\sqrt{\left[\frac{c^2 + 2ax - a^2}{c^2 - (x - a)^2}\right]} \times \frac{(c^2 + 2ax - a^2)[-2(x - a)] - \{c^2 - (x - a)^2\}2a}{(c^2 + 2ax - a^2)^2}$$

This reduces to

$$\frac{dk}{dx} = \frac{-x\,(c^2 + ax - a^2)}{[c^2 - (x - a)^2]^{1/2} \times (c^2 - 2ax - a^2)^{3/2}}$$

This is equal to zero, and k is a maximum when

$$c^2 + ax - a^2 = 0$$

i.e. $\quad x = (a^2 - c^2)/a$

Hence the maximum power factor

$$= \frac{\sqrt{\left[c^2 - \left(\dfrac{a^2 - c^2 - a^2}{a}\right)^2\right]}}{\sqrt{[c^2 + 2(a^2 - c^2) - a^2]}} = \frac{c}{a}$$

Hence for the cascade set we have for the maximum power factor

$$\frac{d}{4\sigma\,(2\sigma + 1)} \div \left\{d + \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)\,(2\lambda_1\lambda_2 - 1)}\right\}$$
$$= \frac{1}{8\sigma^2 + 8\sigma + 1}$$

For a single motor we have the maximum power factor equal to

$$\frac{d}{2\sigma} \div \left(d + \frac{d}{2\sigma}\right) = \frac{1}{2\sigma + 1}$$

Hence

$$\frac{\text{Max. power factor of the set}}{\text{Max. power factor of single motor}} = \frac{2\sigma + 1}{8\sigma^2 + 8\sigma + 1}$$

The value of this ratio depends entirely upon the value of the dispersion coefficient. Hobart* gives a table showing the values of σ for a large number of motors. For medium-sized and large machines it varies between 0·022 and 0·176. The above ratios for these values of σ are 0·885 and 0·557. This shows the great objection to the cascade method of speed control, and the necessity of very careful design of the magnetic circuits if this system is to be adopted.

* "Electric Motors," 2nd ed., p. 478.

Comparisons of torque and power factor for any value of the intake are best shown by plotting these two quantities against a current base.

Expressed in polar co-ordinates we have, from Fig. 5,

$$\text{power factcr} = \sin\theta$$
$$\text{current} = r$$
$$c^2 = a^2 + r^2 - 2ar\cos\theta$$
$$\cos\theta = \frac{a^2 + r^2 - c^2}{2ar}$$
$$\sin\theta = \sqrt{\left[1 - \left(\frac{a^2 + r^2 - c^2}{2ar}\right)^2\right]}$$

quantity d, namely, the magnetizing current of a single motor, we have

$$c_1 = \frac{d}{4\sigma(2\sigma + 1)}$$
$$a_1 = d + \frac{(4\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} = \frac{d(8\sigma^2 + 8\sigma + 1)}{4\sigma(2\sigma + 1)}$$
$$c_2 = \frac{d}{2\sigma}; \quad a_2 = \frac{d(2\sigma + 1)}{2\sigma}$$

Also the range of r for a single motor will be from d to $(d + d/\sigma)$, that is from d to $d(1 + \sigma)/\sigma$.

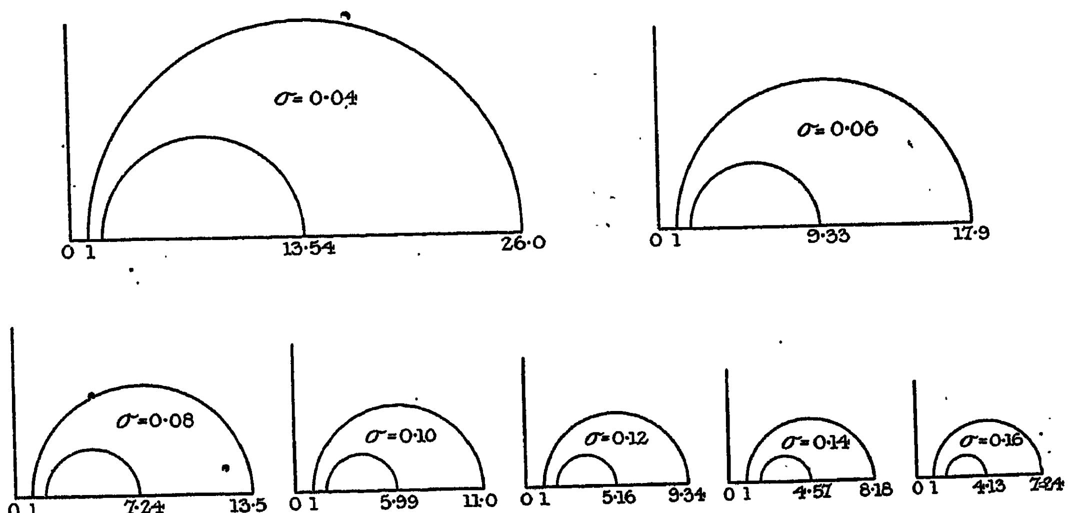

FIG. 6.—Circle diagrams for single induction motors and for two equal motors in cascade.
Outer circle—single motor. Inner circle—cascade motor.

Calling the values of c and a, c_1 and a_1 for the cascade set, and c_2 and a_2 for a single motor we have

Power factor of cascade set

$$K_1 = \sqrt{\left[1 - \left(\frac{a_1^2 + r^2 - c_1^2}{2a_1 r}\right)^2\right]}$$
$$= \frac{\sqrt{(2a_1^2r^2 + 2a_1^2c_1^2 + 2c_1^2r^2 - a_1^4 - r^4 - c_1^4)}}{2a_1 r}$$

Torque of cascade set

$$T_1 = h_1 = r\sin\theta = r \times K_1$$
$$= \frac{\sqrt{(2a_1^2r^2 + 2a_1^2c_1^2 + 2c_1^2r^2 - a_1^4 - r^4 - c_1^4)}}{2a_1}$$

in arbitrary units.

Similarly for the single motor we have

Power factor
$$K_2 = \frac{\sqrt{(2a_2^2r^2 + 2a_2^2c_2^2 + 2c_2^2r^2 - a_2^4 - r^4 - c_2^4)}}{2a_2 r}$$

Torque $T_2 = \dfrac{\sqrt{(2a_2^2r^2 + 2a_2^2c_2^2 + 2c_2^2r^2 - a_2^4 - r^4 - c_2^4)}}{2a_2}$

in arbitrary units.

Expressing c_1, a_1, c_2 and a_2 in terms of the fixed

Practically all actual cases will be covered by taking values of σ from $0 \cdot 04$ to $0 \cdot 16$, say the following values:

0·04, 0·06, 0·08, 0·10, 0·12, 0·14 and 0·16

The corresponding values of c_1, a_1, c_2 and a_2 are given in Table 1.

In the same table the standstill currents of a single

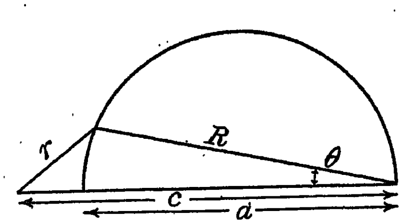

FIG. 7.

motor and of the cascade set are given. The ratio of these currents is approximately 2 : 1 in all cases. The relative sizes of the circles are clearly shown in Fig. 6, which is drawn to scale.

In Table 2 the torques, power factors and ratios of the torques and power factors are worked out for each value of σ and plotted against a current base in

Figs. 8 to 11. Fig. 8 shows the torque T_1 of a cascade set in arbitrary units, while Fig. 9 gives the torque T_2 of a single motor. The inferiority of the cascade set is at once evident from a comparison of these curves.

TABLE 1.

The Unit in which the Quantities c_1, a_1 and Standstill Current are expressed is the Magnetizing Current of a Single Motor.

σ	Cascade motors			Single motor		
	c_1	a_1	Current at standstill	c_2	a_2	Current at standstill
0·04	5·8	7·74	13·54	12·5	13·5	26·0
0·06	3·72	5·61	9·33	8·45	9·45	17·9
0·08	2·69	4·55	7·24	6·25	7·25	13·5
0·10	2·08	3·91	5·99	5·0	6·0	11·0
0·12	1·68	3·48	5·16	4·17	5·17	9·34
0·14	1·395	3·17	4·57	3·59	4·59	8·18
0·16	1·185	2·945	4·13	3·12	4·12	7·24

For currents up to the standstill current of the cascade set the torque of a single motor follows almost a linear law, the droop of the curves being exceedingly small. On the other hand, the curves for the cascade motors

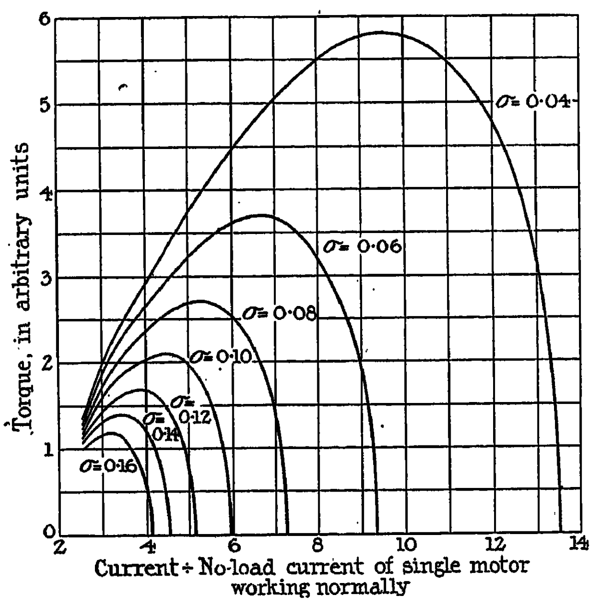

FIG. 8.—Curves showing torque of cascade motors.

droop very quickly, especially those having a high dispersion coefficient.

Fig. 10 gives the power factors K_1 and K_2; here again the inferiority of the cascade motor is apparent, the maximum possible power factor being only 0·75 when the leakage is so small that $\sigma = 0·04$.

Fig. 11 gives the ratios T_1/T_2 $(= K_1/K_2)$.

The study of these curves indicates, perhaps even more emphatically than has already been proved by other investigations, that if induction motors are to be operated in cascade with any success their magnetic circuits must be very carefully designed and every form of leakage reduced to an absolute minimum.

To complete the circle diagram it is necessary to include the circle giving the secondary current of the auxiliary motor. This is worked out as follows:—

Primary current in auxiliary motor
= secondary current in main motor
= GK

Secondary current in auxiliary motor = aC

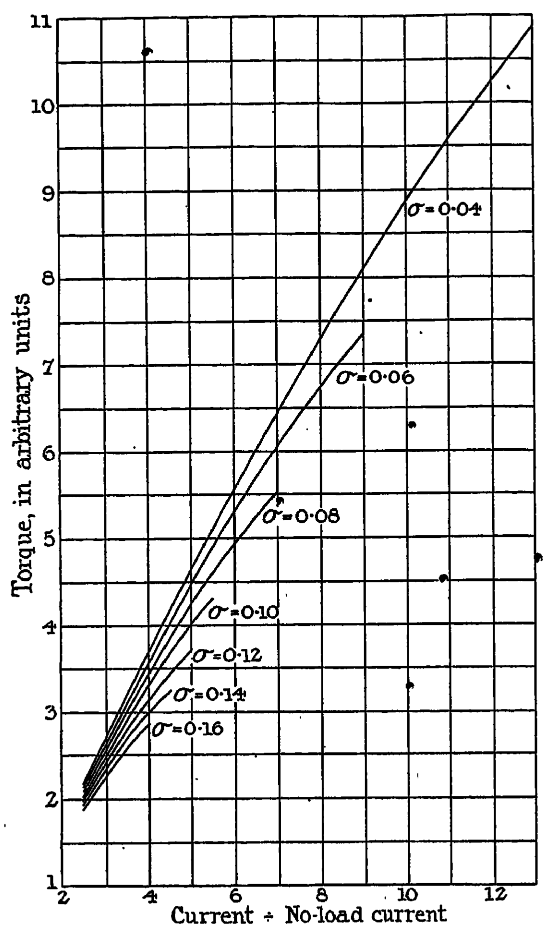

FIG. 9.—Curves showing torque of single motor.

Referred to $x'y'$ axes we have:

x' co-ordinate of point $a = {}_2F_1 \cos \alpha$

y' co-ordinate of point $a = \lambda_1 \, {}_2F_2$

Transforming to xy axes we have, from

$$x = x' \cos \theta + y' \sin \theta \text{ and } y = y' \cos \theta - x' \sin \theta,$$

$$x = {}_2F_1 \cos \alpha \cos \theta + \lambda_1 \, {}_2F_2 \sin \theta$$

$$y = - {}_2F_1 \cos \alpha \sin \theta + \lambda_1 \, {}_2F_2 \cos \theta$$

Now
$$ {}_2F_1 = \frac{d \cos \theta}{(2\lambda_1\lambda_2 - 1) \cos \alpha}$$

and
$$ {}_2F_2 = \frac{d \sin \theta}{2\lambda_1(\lambda_1\lambda_2 - 1)}$$

TABLE 2.

Current r	T_1	K_1	T_2	K_2	$\frac{T_1}{T_2}=\frac{K_1}{K_2}$
		$\sigma = 0·04$			
2·5	1·33	0·532	2·18	0·872	0·61
3	1·95	0·65	2·695	0·90	0·722
4	2·92	0·73	3·684	0·921	0·792
5	3·75	0·75	4·630	0·926	0·82
6	4·464	0·744	5·52	0·92	0·808
7	5·033	0·719	6·405	0·915	0·785
8	5·456	0·682	7·24	0·905	0·755
9	5·742	0·638	8·08	0·898	0·709
10	5·78	0·578	8·85	0·885	0·653
11	5·50	0·50	9·57	0·87	0·574
12	4·80	0·40	10·224	0·852	0·469
13	3·19	0·245	10·85	0·835	0·293
		$\sigma = 0·06$			
2·5	1·26	0·504	2·14	0·856	0·59
3	1·85	0·62	2·63	0·877	0·702
4	2·63	0·658	3·57	0·892	0·739
5	3·24	0·648	4·45	0·89	0·728
6	3·61	0·602	5·28	0·88	0·686
7	3·70	0·529	6·07	0·867	0·61
8	3·30	0·413	6·72	0·840	0·49
9	2·00	0·222	7·33	0·814	0·272
		$\sigma = 0·08$			
2·5	1·22	0·488	2·10	0·840	0·58
3	1·68	0·560	2·56	0·853	0·655
4	2·35	0·589	3·45	0·862	0·680
5	2·67	0·534	4·24	0·848	0·63
6	2·54	0·423	4·92	0·820	0·516
7	1·34	0·191	5·51	0·787	0·243
		$\sigma = 0·10$			
2·5	1·19	0·476	2·07	0·828	0·573
3	1·57	0·523	2·49	0·830	0·631
4	2·03	0·508	3·31	0·828	0·613
5	1·98	0·396	4·0	0·800	0·495
5·5	1·58	0·287	4·31	0·785	0·366
		$\sigma = 0·12$			
2·5	1·13	0·452	2·0	0·800	0·565
3·0	1·45	0·483	2·42	0·807	0·600
3·5	1·63	0·465	2·80	0·800	0·581
4·0	1·68	0·42	3·16	0·790	0·531
4·5	1·49	0·331	3·47	0·772	0·429
5·0	0·83	0·166	3·72	0·744	0·223
		$\sigma = 0·14$			
2·5	1·07	0·428	1·95	0·780	0·559
3·0	1·31	0·437	2·35	0·783	0·558
3·5	1·4	0·399	2·7	0·771	0·519
4·0	1·23	0·308	3·01	0·753	0·408
4·5	0·45	0·100	3·26	0·725	0·138
		$\sigma = 0·16$			
2·5	0·99	0·396	1·88	0·752	0·527
3·0	1·16	0·387	2·26	0·753	0·511
3·5	1·12	0·320	2·58	0·737	0·435
4·0	0·61	0·152	2·84	0·710	0·215

Hence $x = \dfrac{d\cos^2\theta}{(2\lambda_1\lambda_2 - 1)} + \dfrac{d\sin^2\theta}{2(\lambda_1\lambda_2 - 1)}$

$$= \frac{d}{2(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}\left\{2\lambda_1\lambda_2 - 1 - \cos^2\theta\right\}$$

$$= P(4\lambda_1\lambda_2 - 3 - \cos 2\theta)$$

$= x$ co-ordinate of point G referred to K as origin

Also $y = \dfrac{d\cos\theta\sin\theta}{2(\lambda_1\lambda_2 - 1)} - \dfrac{d\cos\theta\sin\theta}{(2\lambda_1\lambda_2 - 1)}$

$$= \frac{d\cos\theta\sin\theta}{2(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)}$$

$$= P\sin 2\theta$$

$= y$ co-ordinate of point G.

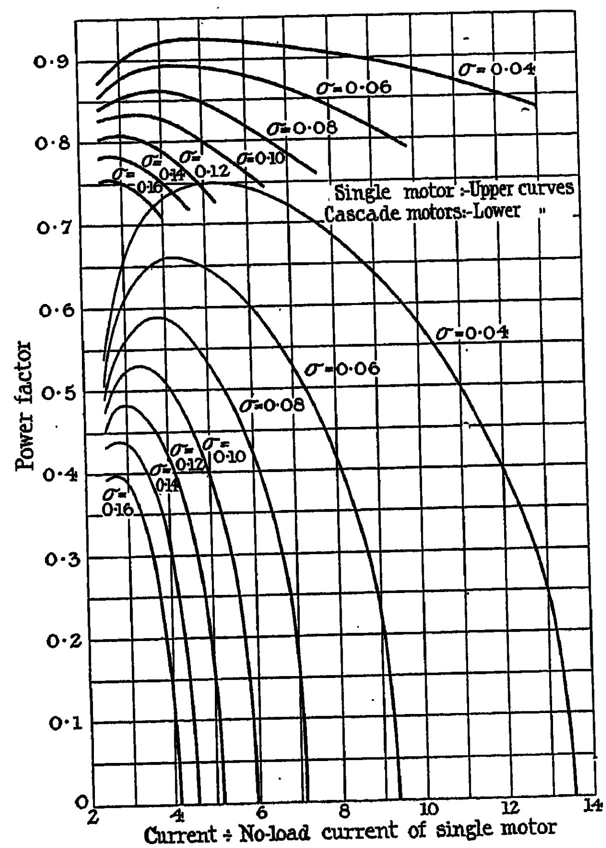

FIG. 10.—Power factor curves.

Hence the vector Oa is always equal and parallel to the vector GK, and points O and G are always located on the x axis.

Again, the locus of G is the current circle of the main motor, hence the locus of "a," i.e. the extremity of the secondary current vector of the auxiliary motor, is a circle with radius equal to that of the main motor circle, and with its centre located on the x axis distant

KL + radius of main motor circle

$$= \frac{4(\lambda_1\lambda_2 - 3)d}{4(\lambda_1\lambda_2 - 1)(2\lambda_1\lambda_2 - 1)} \text{ from the origin.}$$

This circle cuts the x axis at N, where ON = KL.

Now the torque of the main motor is given by the length of the perpendicular dropped from the working point on the stator current circle. Hence the torque of the auxiliary motor will be given by the length of the perpendicular dropped from the working point on the circle representing its own stator current. But these two circles have been proved to be identical (except that the centre of one is displaced along the x axis relatively to the other). Hence the two perpendiculars will be equal, and therefore the torque developed by the auxiliary motor is equal to that of the main motor.

Next consider the locus of the point C, the other extremity of the secondary current vector of the auxiliary motor.

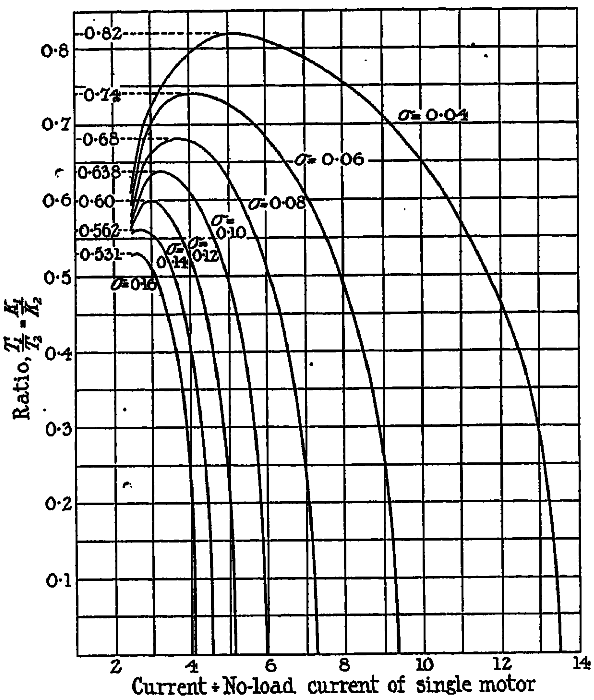

FIG. 11.—Curves showing the ratios of torque and power factor of one of the motors of a cascade set, to the torque and power factor of a single motor.

Referred to $x'y'$ axes we have:

x' co-ordinate $= {}_2F_1 \cos \alpha$; y' co-ordinate $= 0$

Hence referred to xy axes we have

$$x = {}_2F_1 \cos \alpha \cos \theta; \quad y = -{}_2F_1 \cos \alpha \sin \theta$$

Therefore $$x^2 + y^2 = {}_2F_1^2 \cos^2 \alpha = \frac{d^2 \cos^2 \theta}{(2\lambda_1\lambda_2 - 1)^2}$$

and $$OC = \sqrt{(x^2 + y^2)} = \frac{d}{(2\lambda_1\lambda_2 - 1)} \cos \theta$$

This is in the form of the polar equation to a circle, hence the locus of C is a semicircle of radius $\dfrac{d}{2\lambda_1\lambda_2 - 1}$ with its centre on the x axis distant $\dfrac{d}{2(2\lambda_1\lambda_2 - 1)}$ from the origin.*

* It should be noted that although C lies on a semicircle on Oa($= {}_2F_1$) as diameter, this semicircle is only drawn to help in the construction of the diagram. It is not a fixed semicircle because its diameter ${}_2F_1$ is not fixed.

Now the angle OCN is a right angle; hence, since ON lies along the x axis, ON must be the diameter of the semicircle which gives the locus of C. Therefore N is a fixed point, distant $\dfrac{d}{(2\lambda_1\lambda_2 - 1)}$ from the origin.

But $$\lambda_1\lambda_2 = 1 + \sigma$$

Therefore $$ON = \frac{d}{2\sigma + 1} = KL$$

Hence the semicircles giving the locus of the points "a" and "c" are tangential at N.

The change of phase of the voltage applied to the auxiliary machine can be deduced from the diagram. The supply voltage is represented in phase by the OY axis, which is fixed; the P.D. applied to the auxiliary motor is represented in phase by the perpendicular to its magnetizing current, that is by the perpendicular to OD. Hence the difference in phase $= \angle POD = \beta$, say, (see Figs. 2 and 3).

Let $$\angle DOQ = \gamma$$

Now GK is equal and parallel to OA

Therefore $$\angle GKL = \angle AOL = (\alpha - \theta)$$

Again, joining GL, we have GL parallel to aN.

Therefore $$\angle KGL = \angle OaN = \angle aOY' = 90 - \alpha$$

Also $$\angle GKL = 180 - \{(\alpha - \theta) + (90 - \alpha)\} = 90 + \theta$$

Therefore $$\angle GML = \theta$$

Hence, as the current changes from no load to standstill, θ varies from 0° to 90°.

The co-ordinates of D with respect to the $x'y'$ axes are:

$$x' = \lambda_2\, {}_2F_1 \cos \alpha; \quad y' = {}_2F_2\, (\lambda_1\lambda_2 - 1)$$

Therefore $$\tan \gamma = \frac{y'}{x'} = \frac{{}_2F_2\,(\lambda_1\lambda_2 - 1)}{\lambda_2\, {}_2F_1 \cos \alpha}$$

$$= \frac{(\lambda_1\lambda_2 - 1) \tan \alpha}{\lambda_1\lambda_2}$$

since $\lambda_1 \cdot {}_2F_2 = {}_2F_1 \sin \alpha$.

Now $\cos \alpha \sin \theta\, (2\lambda_1\lambda_2 - 1) = 2 \sin \alpha \cos \theta\, (\lambda_1\lambda_2 - 1)$

Therefore $$\tan \alpha = \frac{(2\lambda_1\lambda_2 - 1) \sin \theta}{2(\lambda_1\lambda_2 - 1) \cos \theta}$$

$$= \frac{(2\lambda_1\lambda_2 - 1)}{2(\lambda_1\lambda_2 - 1)} \tan \theta$$

Therefore $$\tan \gamma = \frac{(\lambda_1\lambda_2 - 1)\,(2\lambda_1\lambda_2 - 1)}{2\lambda_1\lambda_2\,(\lambda_1\lambda_2 - 1)} \tan \theta$$

$$= \frac{2\sigma + 1}{2\sigma + 2} \tan \theta$$

$$= K \tan \theta \text{ (say)}$$

Hence, as the current varies from no load to standstill, γ varies from 0° to 90°, and therefore the phase of the potential difference applied to the auxiliary motor relative to the supply potential difference, which is given by the angle $\beta (= \theta - \gamma)$, varies from 0° to a maximum, and then falls to 0° again.

The expression for β is worked out as below, although it is of greater theoretical than practical value.

Let the quantities r, R, c and a have the significance shown in Fig. 7. Then

$$R = a \cos \theta$$

$$r^2 = R^2 + c^2 - 2Rc \cos \theta = a^2 \cos^2 \theta + c^2 - 2ac \cos^2 \theta$$

Therefore $$\cos^2 \theta = \frac{c^2 - r^2}{2ac - a^2}$$

and $$\tan^2 \theta = \frac{r^2 - (c-a)^2}{c^2 - r^2}$$

Again, $$\tan(\theta - \gamma) = \frac{\tan\theta - \tan\gamma}{1 + \tan\theta \tan\gamma} = \frac{(1-K)\tan\theta}{1 + K\tan^2\theta}$$

$$= \frac{(1-K)\sqrt{\left[\dfrac{r^2-(c-a)^2}{c^2-r^2}\right]}}{(1-K)\left\{\dfrac{r^2-(c-a)^2}{c^2-r^2}\right\}}$$

Therefore

$$\beta = (\theta - \gamma)$$

$$= \tan^{-1}\left[\frac{(1-K)\sqrt{[(c^2-r^2)\{r^2-(c-a)^2\}]}}{(c^2-r^2) - K\{r^2-(c-a)^2\}}\right]$$

This is equal to zero when

$r = (c - a)$, the no-load current,

or when $r = c$, the standstill current.

PROCEEDINGS OF THE INSTITUTION.

24TH MEETING OF THE WIRELESS SECTION, 8 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

Professor G. W. O. Howe, D.Sc., Chairman of the Wireless Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 7th June, 1922, were taken as read, and were confirmed and signed.

A paper by Mr. R. L. Smith-Rose, M.Sc., Associate Member, and Mr. R. H. Barfield, B.Sc., Student, entitled "The Effect of Local Conditions on Radio Direction-Finding Installations" (see page 179), was read and discussed and the meeting terminated at 7.45 p.m.

687TH ORDINARY MEETING, 16 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 2nd November, 1922, were taken as read, and were confirmed and signed.

Messrs. J. W. Fyfe and A. H. Allen were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Members.

Clark, George Muirhead.
Farmer, Frank Malcolm, M.E.

Associate Members.

Allen, Francis John C.
Andean, Thomas John.
Andrews, Edward.
Bagnold, Ralph Alger, Capt., R.C.S.
Banks, John
Baxter, William.
Boelsterli, Arthur.
Brown, Arthur.
Bryant, Harold Samuel.
Clark, Frederick Henry.
Clissold, George William U.
Cooke-Smith, Henry.
Currie, Duncan Douglas.
do Amaral, Augusto Basto F.

Associate Members—continued.

Earnshaw, Vincent Rees.
Eugster, Hans.
Ford, Albert Edwin.
Frampton, Frank Edward.
Griffiths, William.
Holbeach, Constantine Hugh.
Joscelyne, Alfred Bamford.
Lee, Robert Henry.
Minton, Richard Caldwell, B.Sc.
Newton, Charles Ernest.
Noyes, Henry Sebastian.
Orling, Axel.
Osborn, William Marshall.
Parsons, Reginald Cole, B.Sc.
Pearse, Harold Leslie.
Ross, William.
Rowell, William Nelson.
Sell, Lawrence Jordan.
Smith, Dugald, B.Sc. (Eng.).
Triggs, Edward Harold H.

Graduates.

Atkinson, Wellesley Sharpe.
Bassett-Lowke, Harold Austin.
Bournes, Norman.
Bunting, Rowland.
Cook, Frederick Charles.
Dixon, Charles Douglas H.
Earle, Robert Erasmus.
Faulkner, Arthur Spencer.
Llewellyn-Jones, Ivor.
Lowe, Walter.
McGrath, Francis Albert, B.E.
Rogers, Henry Kenneth.
Rowson, Leslie.
Witt, Sidney Herbert.

Students.

Abbott, Albert James.
Anderson, Charles.
Anderson, John Robertson.
Andrew, Thomas Stuart.
Baggaley, Cyril Frank.
Ball, Reginald Donahoe.
Bell, William Henry H.
Benjamin, Albert Hansen.
Bennett, Wilfred.
Booth, William Leslie.
Bowers, Wilfred Edward H.
Bowker, Eric George.
Brewer, Arthur.
Brewin, James Edwin.
Britnell, Wilfred Varney.
Bryan, Ernest Alfred J.
Carter, Charles John E.
Chakravarti, Girindra Narayan.
Challr, Stewart Leonard.
Clarke, Henry Rowland.
Clewett, William Henry.
Clinton, James Stanley.
Cocks, Maurice Hubert.
Collyns, Charles Henry A.
Cooke, Conrad Reginald.
Couch, Charles John.
Das, Jatindranath.
Datta, Naren, B.Sc.
Donaldson, Thomas.
Eccleston, Robert John.
Ellis, Arthur Eric.
Ellis, Cecil Maurice.
Ellis, Harold.
Fewings, William Francis.
Fothergill, John Buddle.
Francis, Richard Brynmor.
Goodman, Reginald Alfred.
Gresswell, William Finlay.
Hardy, George Gordon.
Hellier, William Herbert M.
Heslop, John Pattison.
Hogg, William.
Horsfall, Leslie A.
Innes, James Albert.
Johnson, Eric Mark.
Keeley, Donald.
Lewis, Walter.
Lisle, Patrick St. John.
Lockett, Thomas Herbert.
McCulloch, Reginald Andrew.
McNab, John.
Manning, Charles Joseph.
Matthews, Leslie Albert.
Miller, William Henry.
Mitchell, Henry Lloyd.
Mitchell, Wallis.
Morgan, Cecil Montagu.
Mossman, Conrade Eric.
Parsons, Albert George.
Pearce, Ivor Stanley.
Peel, Edward Ullathorne.
Penn, Herbert Austin.
Reed, Arthur Weston.
Rees, Handel.
Reynolds, Leigh Travis.
Ross, Burton William.
Ryder, John Hampson, B.Eng.
Scott, William George, B.Sc. (Eng.).
Simpson, Henry Greeff.
Smith, Cyril Belfield.
Smithson, Alfred.
Stainsby, James William.
Tucker, Dan Keith.
Wheeler, Henry.
Williams, Alec Duncan.
Williamson, Arthur.
Wolfe, Standish Smythe.
Wood, George William.
Woodford, Charles George A.

TRANSFERS.

Associate Member to Member.

Davis, Albert Lewis, Capt., R.A.F.
Lee, Harrie Tomlinson.
Slater, John Mackey L.
Wilson, William.

Associate to Member.

Bell, John Edward.
Starling, Frank Henry.
Swallow, Maurice Gustave S.

Graduate to Associate Member.

Berriman, Robert Harrold.
Calogreedy, Henry Charles.
Davison, Russell Hawes.
Firth, Charles Roy H., Lieut.
Larkworthy, Ralph.
Leaver, Henry.
Messer, William Gustave.
Rogers, Arthur Harry E.
Sparks, Cedric Harold.

Student to Associate Member.

Balmford, Edgar.
Field, Harold Victor.
Millner, William, B.Sc.

Associate to Associate Member.

Barnes, Cuthbert Wheeldon.
Naftel, Percy Hartley.
Read, Richard Francis.
Smart, William Charles.

Student to Graduate.

Armstrong, Stanley Ignatius.
Blazey, Norman Claude.
Boldy, Tigran David.
Butler, Archibald Stephen.
Gabbott, Thomas.
Molle, George William.
Morcom, Herbert Geoffrey.

The following list of donations was taken as read, and the thanks of the meeting were accorded to the donors :—

Library.—The Air Ministry (Meteorological Office), The American Rolling Mill Company, The Astronomer Royal, A. H. Avery, Lieut.-Col. B. C. Battye, Messrs. Benn Brothers, Ltd., E. Bennett, Ch. Beranger, Messrs. Blackie & Son, Ltd., The Borough Electrical Engineer of Stepney, The British Engineering Standards Association, The Bureau of Mines (British Columbia), F. W. Carter, The Chief Inspector of Factories and Workshops, Messrs. Constable & Co., Ltd., The Electrical Press, Ltd., W. Haddon, P. J. Haler, The High Commissioner of the Union of South Africa, The Imperial Mineral Resources Bureau, The Institution of Professional Civil Servants, The Institution of Railway Signal Engineers, The Institution of Royal Engineers, The John Fritz Medal Board of Award, P. Kemp, A. E. Kennelly, The Lancashire and Cheshire Coal Research Association, Messrs. S. Lattes & Co., Lloyd's Register of Shipping, Messrs. Longmans, Green & Co., F. W. Main, J. W. Meares, C.I.E., Messrs. Oerlikon, Ltd., Lieut.-Col. W. A. J. O'Meara, C.M.G., R.E., L. Oulton, Pan-American Petroleum and Transport Co., E. Parry, L. J. Peters, Messrs. Sir Isaac Pitman & Sons, Ltd., Messrs. Radio Instruments, Ltd., Messrs. S. Rentell & Co., Ltd., The Signals Experimental Establishment (Woolwich), C. F. Smith, The Surveyor-General of India, Messrs. E. & F. N. Spon, Ltd., W. T. Taylor, Union d'Électricité, H. E. Wimperis, The Wireless Press, Ltd., and A. P. Young.

The President: I have to announce that the Council have unanimously elected Professor J. A. Fleming an Honorary Member of the Institution. Dr. Fleming is so well known to all of you that almost anything I could say would be superfluous, but the fact that one of the first announcements I have to make as President is that he has been elected an Honorary Member is a great pleasure to me, particularly because of his researches in connection with the thermionic valve.

I have also to announce that, with the object of encouraging more spontaneous discussion, in future not more than two or three members will be invited officially to take part in discussions and that the Council will rely on other members coming forward to speak.

A paper by the late Dr. Gisbert Kapp, Past-President, entitled "The Improvement of Power Factor" (see page 89), was read by Prof. Miles Walker and discussed, and the meeting terminated at 7.45 p.m.

A DIRECT-READING THERMIONIC VOLTMETER, AND ITS APPLICATIONS.

By E. B. MOULLIN, M.A.

(*Paper received 2nd November, and read before the* WIRELESS SECTION *6th December*, 1922.)

SUMMARY.

The conditions suitable for constructing a sensitive direct-reading voltmeter from a triode rectifier are discussed and two distinct forms of completed thermionic voltmeter are described. The power absorbed by a rectifier is discussed theoretically, and a description is given of the experimental methods of measuring the effective resistance of a thermionic voltmeter. Possible causes of frequency errors in the calibration of the voltmeter are considered and the results of experiments are quoted, showing that a calibration made at low frequencies is reliable up to at least one million periods per second. Several typical illustrations are given of the uses of a thermionic voltmeter in measurements at both high and low frequencies.

TABLE OF CONTENTS.

(1) INTRODUCTION.

There are many occasions in alternating-current work when it is desirable to measure small electromotive forces of the order of one or two volts; such measurements are attended with great difficulty in cases where it is essential that they shall not absorb any appreciable power from the circuit that is being tested. Practically the only instrument hitherto available has been that most useful piece of apparatus an alternating-current potentiometer, but the use of this is precluded in measurements at high frequency.

The well-known thermionic vacuum tube forms a most convenient method of measuring alternating electromotive forces of any frequency, because owing to its asymmetric conductivity an alternating E.M.F., of which the mean value is zero, produces an alternating current whose mean value is not zero, and the said mean value is readily measured by an ordinary milliammeter or micro-ammeter. A rectifier and galvanometer have long been used in laboratory measurements as a rough indicator for high-frequency work.

If a suitably arranged three-electrode vacuum tube is used as the asymmetric conductor, the measurements need not absorb any power from the circuit that is tested, for the power absorbed by the micro-ammeter is provided by a subsidiary battery.

The two methods of using the triode valve as a rectifier are well known: one method employs the curvature of the anode current/grid potential characteristic, while the other method employs the curvature of the grid current/grid potential characteristic.

(2) CONDITIONS SUITABLE FOR USING A TRIODE RECTIFIER AS A DIRECT-READING VOLTMETER.

There exists, as well as the change of mean anode current that arises from the application of an alternating E.M.F. between grid and filament, an anode current produced solely by the anode battery; consequently, unless the change of mean anode current arising from the alternating E.M.F. that is to be measured is of the same order as the anode current flowing under the action of the anode battery, it cannot be satisfactorily measured by a galvanometer placed direct in the anode circuit. This is particularly the case when employing the curvature of the anode current characteristic under the conditions which make for the greatest possible change of mean anode current for a given alternating E.M.F. applied to the grid. For example, an anode battery of 50 or 60 V will, in an R triode, produce an anode current of about 1 000 μA, and an E.M.F. of 1·5 volts (R.M.S.) applied to the grid will then increase the mean anode current by about 30 μA. In order that this comparatively small change in mean anode current can be accurately measured, some balance method must be employed.*

A balance method, though very suitable for many laboratory measurements, does not lend itself to the construction of a simple and portable direct-reading voltmeter. In such an instrument, unlike a rectifier for wireless signals, the aim is to make the change of mean anode current consequent upon the application to the grid of some specified E.M.F. as large as possible in comparison with the anode current flowing under the action of the anode battery.

* See E. B. MOULLIN and L. B. TURNER: "The Thermionic Triode as Rectifier," *Journal I.E.E.*, 1922, vol. 60, p. 708.

With a cumulative grid rectifier, an alternating E.M.F. of 3 volts can be made to produce a decrease of mean anode current of about 500 μA when the anode current produced by the anode battery is about 1 000 μA; consequently, a galvanometer placed direct in the anode circuit can be used to measure the change produced by the application of an alternating E.M.F., and there is no need to use a balance method.

An anode curvature rectifier may be employed without balance method if the usual anode battery is dispensed with, and the anode connected through a galvanometer to the positive side of the filament. An E.M.F. of 1·5 volts (R.M.S.) applied to the grid will then produce an increase of mean anode current of about 10μ A. If a 50-volt anode battery had been employed, this increase instead of being 10 μA would have been 30 μA, which is about 4 per cent of the anode current flowing under the action of the anode battery; but the 10 μA change with no anode battery is a 400 per cent increase on the anode current flowing when the anode is simply connected to the positive side of the filament, a condition particularly suitable for using a triode as a simple voltmeter. The lack of anode battery is not only suitable in this respect but it obviously increases the portability of the instrument.

(3) Description of Completed Instruments.

Fig. 1 shows a completed instrument working with grid rectification, and Fig. 2 a diagram of connections. It is found that the calibration is inappreciably affected by small changes of anode or filament voltages, so that there is no necessity to reproduce accurately the conditions obtaining at the time of calibration.* Since the change of mean anode current consequent upon the application of a given E.M.F. to the grid is sensibly independent of small changes of anode potential, it is possible to adjust for these small changes by means of the zero adjuster of the galvanometer. With the valve switched on and the anode battery connected, the pointer is simply brought to the zero of the scale, which in this case corresponds to the full deflection of the instrument.* One special advantage of this type of instrument is that it is unaffected by the existence of a steady potential difference between its terminals; it can, in consequence, be used to measure an alternating E.M.F. superposed upon a steady E.M.F. of large or small value.

Fig. 3 shows an instrument utilizing anode current curvature for rectification. No separate anode battery is employed and all that is required to complete the instrument for use is a 6-volt filament battery. The instrument is very robust mechanically and, unlike thermo-couples, it cannot be injured by an overload. It is also as easy to use and almost as portable as an ordinary direct-current voltmeter.

Fig. 4 shows a diagram of connections, from which it will be seen that the 6-volt filament battery is not used to apply 6 volts to the filament, but to provide a means of making the grid potential 1·6 V negative, in order to reduce grid damping to a negligible amount. This method of fixing the grid potential allows it to be made about 0·25 V more negative than it could have been if a single small dry cell were used for the purpose, and it also obviates the risk of the calibration being upset by the deterioration of a small cell.

In order to ensure an indefinitely long life to the valve, only 3·6 V is applied to the filament; this is also the case with the cumulative grid type instrument already described.

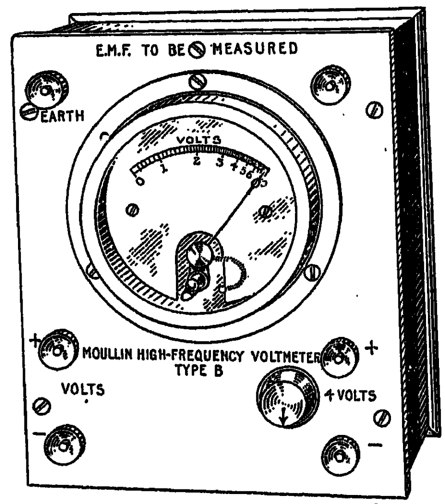

Fig. 1.

The rate of change of mean anode current with respect to alternating grid potential tends to increase and so a high resistance is inserted in the anode circuit with a view to improving the linearity of the scale and thereby increasing the range of the instrument; it does not, however, reduce the sensitivity of the first part of the scale. It is readily seen that by causing

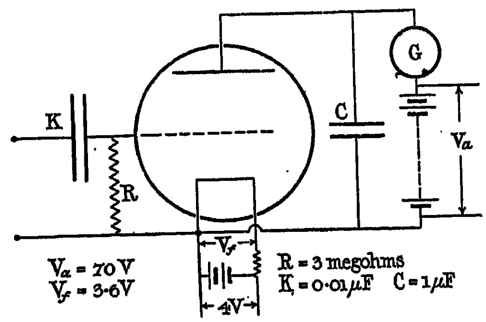

Fig. 2.

the increasing mean anode current to pass through a high resistance the mean potential of the anode is decreased by an amount that is proportional to the increase of mean anode current. The rate of increase of mean anode current is lessened by the reduction of anode potential, and by a suitable choice of anode resistance the volt scale can be made as nearly linear as may be desired.

A typical calibration curve is reproduced in Fig. 5 and is seen to be very nearly straight over the greater

* For a more detailed description of this instrument, see *Wireless World and Radio Review*, 1922, vol. 10, p. 1.

part of the range. The voltmeter is of course used without a calibration curve and, as may be seen in Fig. 3, its scale is engraved direct in volts.

Since the filament battery is the only variable factor in the whole instrument the constancy of the calibration depends on it alone. The exact conditions obtaining at the time of calibration are readily reproduced by

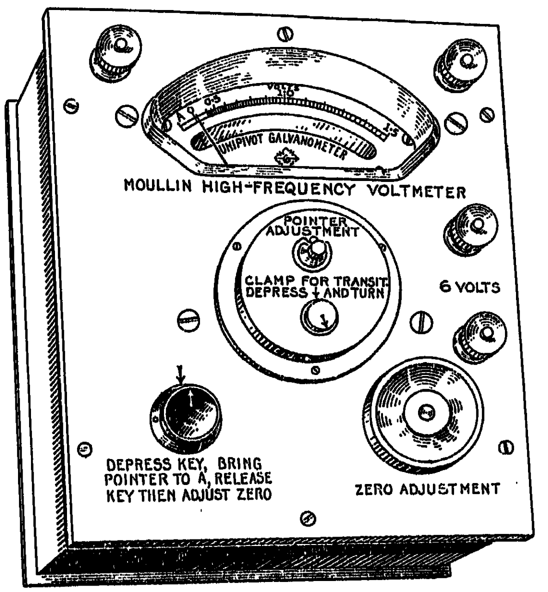

FIG. 3.

means of the filament rheostat and the indications of the galvanometer. Having ascertained that a conducting path exists between the "volt terminals" of the instrument so as to ensure that the potential of the grid will be fixed, the valve is switched on and the filament rheostat adjusted so as to bring the galvano-

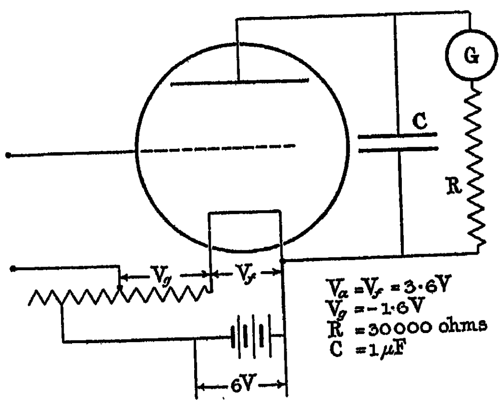

FIG. 4.

meter to the zero of the volt scale, which, as can be seen in Fig. 3, does not correspond to the zero of the galvanometer, marked "A." When this adjustment has been made, the anode current flowing is the same as at the time of calibration, and as this depends solely on the grid, filament and anode potentials, all of which in this instrument depend on the filament current only, the conditions obtaining at calibration are accurately reproduced. If the filament current had been greater than at the time of calibration the galvanometer would have deflected further than the zero of the volt scale, and vice versa.

It will be noticed that a conducting path must at all times exist between the "volt terminals" of the instrument, for otherwise the grid potential will not be correct. For example, this type of voltmeter cannot be used to measure the potential difference across one of two condensers in series, for it is then converted into a cumulative grid rectifier, and the calibration is upset. Also the calibration is obviously upset if any steady potential difference exists between the "volt terminals." Neither of these slight disabilities is shared by the form of voltmeter shown in Fig. 1, so that there are certain points in favour of the less portable form of instrument.

A triode can be used to measure an alternating E.M.F. by employing what is usually called the "slide-back method of measurement." It has several times

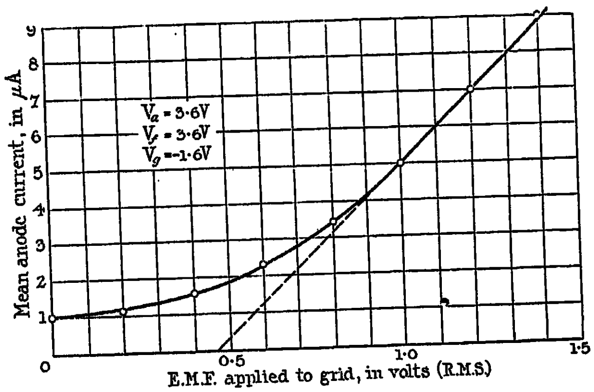

FIG. 5.

been shown that the value of the "slide-back voltage" is not a direct measure of the E.M.F. applied to the valve; consequently, unless calibrated, the slide-back method cannot be considered to be anything but a rough indicator, and if calibrated it suffers from the disability of having a large personal factor in deciding on the appropriate slide-back. It is difficult to make direct reading and is not very portable, as it entails cumbersome grid and anode batteries and a d.c. voltmeter, as well as a galvanometer.

F. Trautwein has described * a form of voltmeter in which, like the slide-back, the effect of the anode battery is nullified by making the grid 10 or 11 V negative. Instead of making the grid still more negative when the E.M.F. is applied, and so again reducing the anode current to zero, the mean anode current is taken as a measure of the E.M.F. The portability is again impaired by cumbersome batteries, and the early part of the calibration must be affected appreciably by small changes in battery voltage.

Messrs. A. E. and L. Bloch have described † a voltmeter using cumulative grid rectification, in which the

* *Telegraph und Fernsprech Technik*, 1921, vol. 10, p. 81.
† *Bulletin de la Société française des Electriciens*, 1920, vol. 10, p. 9.

change of mean anode current, consequent upon the application of an alternating E.M.F. to the grid, is measured by a balance method equivalent to that referred to in Section (2) above. The voltmeter proper is preceded by a two-stage resistance amplifier, the amplification of which must depend to a great extent upon the frequency. Messrs. Bloch recommend that the instrument should always be calibrated at the frequency to be used.

The outstanding feature of the author's form of grid-type voltmeter is that the anode battery is chosen so that the decrease of mean anode current bears a maximum ratio to the anode current produced by the anode battery, thus allowing balance methods to be dispensed with and the instrument dial to be calibrated direct. This is also the condition which makes the calibration sensibly independent of small changes in the E.M.F.'s of the batteries or in the grid leak resistance. A very simple direct-reading instrument results, and no special care need be taken to reproduce closely the calibrating conditions. The outstanding points about the author's form of anode type voltmeter are, first, the complete absence of separate anode or grid batteries, the only extraneous apparatus required being a nominally 6-volt accumulator: and secondly, the exact reproduction of the calibrating conditions by the indication of the galvanometer. So far as the author is aware, the methods of application and construction of both types are original, and he believes that they make simpler and more portable instruments than anything yet described.

(4) The Power Delivered by an Alternating E.M.F. to an Asymmetric Conductor.

The two great advantages of a thermionic voltmeter are, first, that its readings are independent of frequency, and, secondly, but of no less importance, that it can be made to absorb negligible power from a circuit. The effective resistance of both types of instrument can be measured, but it is interesting to obtain a theoretical expression for the power absorbed by an asymmetric conductor.

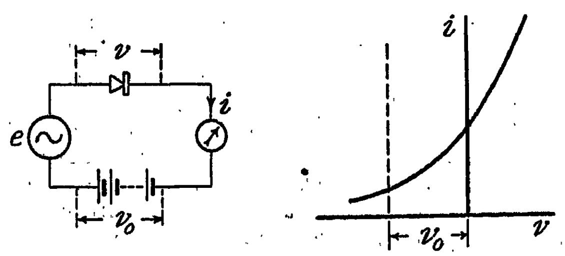

Fig. 6.

Let the asymmetric conductor (Fig. 6) have a curved characteristic $i = f(v)$ which can be represented by a convergent infinite series.

Then
$$v = v_0 + e$$
and
$$i = f(v_0) + ef'(v_0) + \frac{e^2}{2!}f''(v_0) + \frac{e^3}{3!}f'''(v_0) + \dots$$

Let
$$e = a \sin pt$$
then
$$i = f(v_0) + a \sin pt f'(v_0) + \frac{a^2 \sin^2 pt}{2!}f''(v_0) + \frac{a^3 \sin^3 pt}{3!}f'''(v_0) + \dots$$
and
$$ie = a \sin pt f(v_0) + a^2 \sin^2 pt f'(v_0) + \frac{a^3 \sin^3 pt}{2!}f''(v_0) + \frac{a^4 \sin^4 pt}{3!}f'''(v_0) + \dots$$
$$\therefore \frac{\int_0^{2\pi/p} ie\,dt}{2\pi/p} = \frac{a^2}{2}f'(v_0) + \frac{a^4}{16}f'''(v_0) + \dots$$
$$\therefore \text{mean power} = \tfrac{1}{2}a^2\left\{f'(v_0) + \tfrac{1}{8}a^2 f'''(v_0)\right\}$$
$$= \mathcal{E}^2\left\{f'(v_0) + \tfrac{1}{4}\mathcal{E}^2 f'''(v_0)\right\} \quad \dots \quad (1)$$
where $\mathcal{E}$ = mean-square value of e.

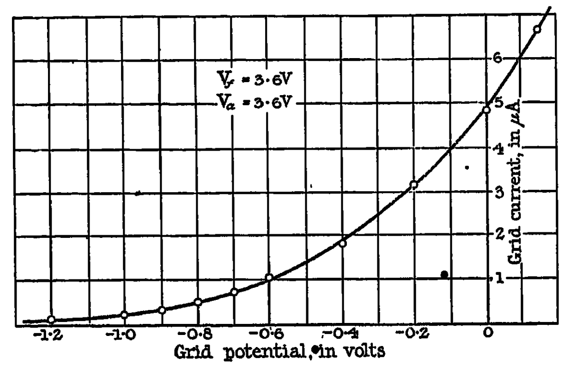

Fig. 7.

The effective resistance is, of course, not a constant but is a function of $\mathcal{E}^2$.

Now, as is well known, the mean value of the current is given by the expression
$$I = \tfrac{1}{2}\mathcal{E}^2 f''(v_0) + \tfrac{1}{16}\mathcal{E}^4 f''''(v_0) + \dots \quad (2)$$

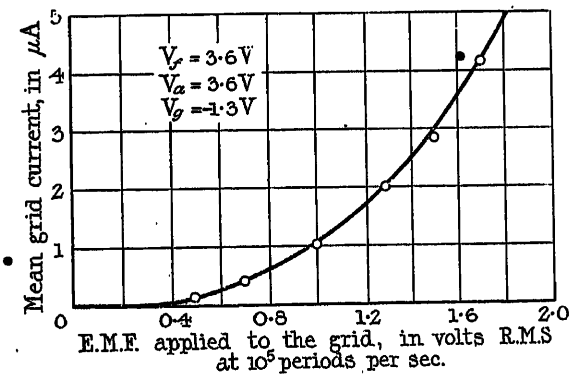

Fig. 8.

so that it is seen that the mean current taken by a rectifier is no indication of the power absorbed by it from the source of alternating E.M.F., except in so far as there may be a relation between $f'(v_0)$ and $f''(v_0)$, $f'''(v_0)$ and $f''''(v_0)$.

Direct high-frequency measurements have been made of the effective resistance of an anode-type voltmeter.

The grid current/grid potential curve for the instrument tested is shown in Fig. 7, while Fig. 8 shows the mean grid current as a function of the E.M.F. (at 10^5 periods per sec.) applied to the grid. From Fig. 7, with or without the help of Fig. 8, it may be found that for a mean grid potential of 1·3 V (negative) the value of $f'(v_0) \fallingdotseq 0{\cdot}35\ \mu A/V$ and that the value of $f'''(v_0) \fallingdotseq 4\mu A/V/V/V$; and hence, from (1) above, the effective resistance $\fallingdotseq \frac{1}{0{\cdot}35 + \mathcal{E}^2}$ megohms. This is approximately 0·75 megohm if $\mathcal{E} = 1$ V, and 0·4 megohm if $\mathcal{E} = 1{\cdot}5$ V.

To make a direct high-frequency test of the effective resistance, a circuit was arranged as in Fig. 9 in which $L = 480\ \mu H$, and $C = 6\ 270\ \mu\mu F$, and R measured at 10^5 periods per sec. (p.p.s.) was 15 ohms. The circuit was fed by a sustained alternating E.M.F. at 10^5 p.p.s., the current in the circuit was measured by a vacuo thermo-junction, and the resonance potential developed across the condenser was measured by an anode-type thermionic voltmeter.

By observing the thermo-junction reading with and without the voltmeter connected across the condenser

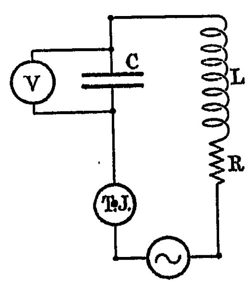

FIG. 9.

it is possible to calculate the effective resistance of the voltmeter. For let the effective resistance of the voltmeter be denoted by r, then the impedance of the circuit consisting of L and R in series with C and r in parallel is given by

$$Z = \sqrt{\left[R^2 + \frac{\omega^2 L^2 + 2Rr}{1 + r^2\omega^2 C^2}\right]} \text{ when } \omega L = \frac{1}{\omega C}$$

$$\fallingdotseq R\sqrt{\left[1 + \frac{2}{Rr\omega^2 C^2}\right]}$$

$$\fallingdotseq R + \frac{1}{r\omega^2 C^2}$$

Hence the proportional increase of impedance caused by placing r in parallel with C is equal to

$$\frac{1}{rR\omega^2 C^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Thus, in the particular circuit tested, this proportionate increase of impedance is equal to $4{\cdot}3 \times 10^3/r$. It was found that by connecting the voltmeter across C, the current as measured by the thermo-junction was reduced by an amount that was certainly less than 1 per cent, when the value of the current was such that the potential difference across C was 1·75 V (R.M.S.). Now, if r had been 0·5 megohm, by (3) above the decrease of current would have been 0·86 per cent, so that even at full scale the effective resistance of the voltmeter is at least half a megohm, and much more at half scale. The power taken at full scale is consequently not more than 6 microwatts. A megohm resistance substituted for the voltmeter caused a decrease in current that was approximately the same as that caused by the connection of the instrument. It may be noted that, in the particular instrument tested, the mean grid potential was only 1·3 V negative, whereas in later instruments it is always made 1·6 V negative, with a consequent increase in the effective resistance.

The effective resistance of the cumulative grid type of voltmeter is slightly greater than in the anode type, because the mean grid potential becomes more and more negative with an increasing alternating E.M.F. applied to the grid; in fact, the calibration shows that with an E.M.F. of 3 V (R.M.S.) applied to the grid, the mean grid potential must be at least 2·5 V negative.

The effective resistance of this type is conveniently measured by making two calibration curves at low frequency: one with a grid condenser, the impedance of which is negligible in comparison with the resistance of the grid leak, and one with a condenser of known and appreciable impedance. From the difference between the two calibrations the effective resistance can readily be calculated.*

As the resistance of either type of voltmeter is at least half a megohm, there are few measurements in which it is necessary to allow for the decrement thereby introduced, as the following example will illustrate.

The decrement introduced into an oscillatory circuit LC by a condenser leak of high resistance r is

$$\delta = \frac{\pi}{r}\sqrt{\left(\frac{L}{C}\right)}$$

Now suppose $L = 2\ 000\ \mu H$ and $C = 200\ \mu\mu F$ (corresponding to $\lambda = 1\ 200$ m) and that $r = 0{\cdot}75$ megohm; then $\delta \fallingdotseq 0{\cdot}015$.

In cases where the decrement introduced by the voltmeter is of importance it can, as already seen, be determined with sufficient accuracy to enable the necessary allowance to be made.

(5) Method of Calibration, and Accuracy Tests at High Frequencies.†

A convenient method of calibrating a voltmeter is by means of a potentiometer slide-wire of known resistance which carries a known alternating current of any frequency. The method is shown diagrammatically in Fig. 10. E is a source of alternating current at high or low frequency. A is an ammeter and R is the potential slide, which may conveniently be arranged in 1-ohm steps. Since in a properly designed thermionic voltmeter the calibration is necessarily independent of frequency, it is most conveniently effected at the low frequencies of ordinary commercial power supply, but, if preferred,

* See "A Sensitive Direct-reading Voltmeter and Ammeter for High Frequencies," *Wireless World and Radio Review*, 1922, vol. 10, p. 1.

† The experiments described in this paper were carried out in the Engineering Laboratory, Cambridge, with facilities put at the author's disposal by Professor C. E. Inglis.

it can of course be made in the same manner at high frequencies. So long as adequate means are provided to ensure that the alternating fluctuations of anode potential are negligible at the highest frequency likely to be met with, then a calibration made at low frequency can always be trusted.

The internal capacities of the triode may cause a quadphase grid current to flow which might appreciably lower the P.D. to be measured, and also the internal

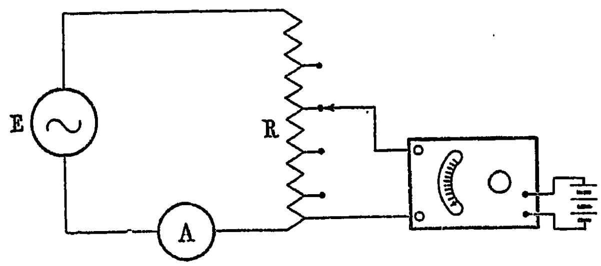

FIG. 10.

capacity will enhance the alternating component of anode current, but so long as a sufficiently large condenser is connected between the anode and the filament there will be no fluctuation of anode potential, and neither internal capacities nor anode-circuit impedances can upset the low-frequency calibration. Many high-frequency tests of the calibration have been made and no appreciable change with frequency is observable. Figs. 11 and 12 relate to high-frequency tests which

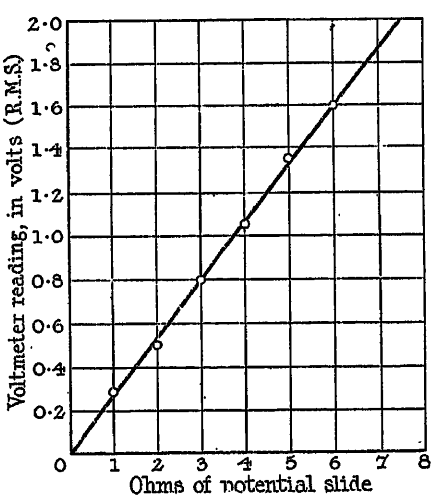

FIG. 11.

were made by measuring the P.D. developed across known resistances by the passage through them of a known high-frequency current. The resistances were constructed from short lengths of fine Eureka wire (36 S.W.G.) and the current was measured by means of a fine wire vacuum thermo-junction.

Fig. 11 shows a relative calibration test of the whole scale at 10^5 p.p.s. The applied E.M.F., as measured by the resistance included between the potential terminals of the potentiometer, is plotted horizontally and the voltmeter reading vertically; it can be seen that the low-frequency calibration is, over the whole range of the scale, truly proportional to the high-frequency E.M.F. applied to the instrument. Fig. 12 shows the result of a test on an anode-type voltmeter of the calibration made at 90 p.p.s.; the percentage inaccuracy of the full-scale reading is shown for frequencies up to half a million per second. Up to 3×10^5 p.p.s. the 90 p.p.s. calibration is certainly correct to less than 1 per cent; at 8×10^5 p.p.s. ($\lambda = 380$ m) the low-frequency calibration seems to be between 3 and 4 per cent too low. This error could not be corrected by indefinitely increasing the shunting condenser in the anode circuit, and it is very probably not due to the voltmeter at all but to the tendency of the thermo-junction to read high with increasing frequency. Of many other high-frequency tests of the voltmeter two more may be cited, one relating to the circuit of Fig. 9 and one to an aerial resistance test. In Fig. 9 the value of the P.D. across C calculated from the capacity, the frequency, and the measured current was 1·7 V, whereas the P.D. observed by the voltmeter was 1·75 V. The resistance at 8×10^5 p.p.s. of a small aerial was measured both by substitution and by injecting a known E.M.F. and measuring by means of the voltmeter the current produced. The substitution

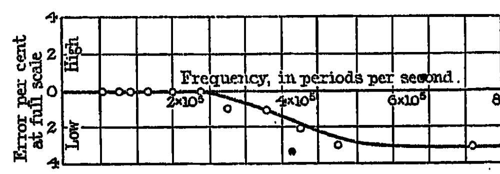

FIG. 12.

method gave the resistance as 30 ohms and the voltmeter method as 27·5 ohms.

The tests and examples quoted above are probably sufficient to prove that the calibration made at low frequencies can certainly be trusted up to very high frequencies, if adequate precautions are taken in the design and construction of the instrument. It has been suggested that low-frequency tests of the general theory of rectification are not applicable to the conditions obtaining at high frequencies;* but the above tests would suggest that this is not the case.

It is no doubt possible to obtain a mathematical expression for the extent of the error produced by the presence in the anode circuit of some stated amount of impedance; but as this impedance can always be indefinitely reduced by a shunting condenser, and in practice will always be so reduced, the result of such an investigation would be of no practical and of little theoretical interest.

That the presence in the anode circuit of a small impedance can have but very small effect on the calibration can be seen in general terms, for the small fluctuations of anode potential must be sensibly in quadphase with the fluctuations of grid potential, and so add and subtract most from the anode current just at the time when it is near its mean value. In the anode type of instrument described above we may,

* See discussion on "The Thermionic Triode as Rectifier," *Journal I.E.E.*, 1922, vol. 60, p. 720.

with great accuracy, assume that current flows only during the positive half-cycle of E.M.F. If the anode-potential fluctuations were exactly in quadphase with the grid potential, then there would be no net change in the area of the half-cycle of anode current. The error must be roughly proportional to the amount by which the anode current is de-phased by the impedance, or to the ratio between the impedance and the mean value of the anode slope resistance. The mean anode slope resistance is about 1 megohm, so that to produce a phase angle of one-tenth of a degree would need, at 10^5 p.p.s., an inductance of 200 μH.

(6) Some Applications of the Thermionic Voltmeter.

A low-reading alternating-current voltmeter of sensibly infinite resistance has a wide range of applications for all sorts of measurements whether at wireless frequencies or telephonic frequencies, or at the frequencies of ordinary commercial power supply. A few typical applications will be dealt with as follows.

(*a*) *As a high-frequency milliammeter.*—By measuring the potential developed across a known inductance or capacity, the current can be calculated if the frequency is known, and in this way the instrument can be used to measure extremely small currents. For example,

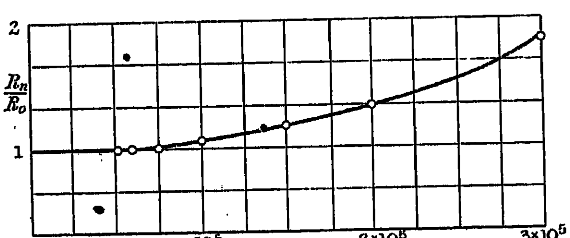

Fig. 13.

at a frequency of 10^5 p.p.s. the current required to develop a P.D. of 1 volt across an inductance of 10 000 μH is about 160 μA. Now, with the most sensitive thermo-junction and portable galvanometer set obtainable, the smallest current that can be measured with the same accuracy with which 1 volt can be measured, on either of the voltmeters described above, is about 5 000 μA; so that under reasonably favourable conditions the voltmeter used as an ammeter gives a sensitivity some 30 times as great as the best thermo-junction set and is equally portable. But, whereas a thermo-junction is very easily burnt out by a small overload, the thermionic voltmeter cannot be damaged by any amount of overloading. It is obvious that the sensitivity may be indefinitely increased by interposing a calibrated amplifier between the voltmeter and the E.M.F. to be measured, but the above example was intended to show the sensitivity of the voltmeter itself without the assistance of extraneous apparatus. [For an example of its use with an amplifier see (*e*) below.] Its superior sensitivity as compared with that of a thermo-junction is often a matter of great practical convenience; for instance, the voltmeter can always be used as an indicator of resonance in a circuit energized inductively from an ordinary buzzer-driven wave-meter. The uniformity of the scale makes it a most convenient instrument for use in plotting resonance curves or for measuring resistances by a substitution method.

(*b*) *Direct measurement of very small self and mutual inductances.*—Inductances of the order of a microhenry are as a rule not readily measured either by bridge or resonance methods, but by passing through them a high-frequency current of some $\frac{1}{2}$ ampere in value they can be measured directly by the use of the voltmeter.

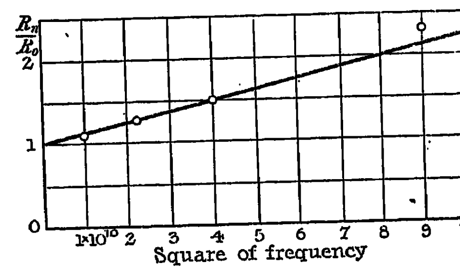

Fig. 14.

As an example, a coil was made consisting of two turns of 32 S.W.G. wire, 6 cm in diameter, the calculated value of the inductance being $1\cdot86\,\mu$H. The value measured by the voltmeter and an ammeter was $1\cdot80\,\mu$H at $1\cdot5\times10^5$ p.p.s. Interesting measurements could perhaps in this way be made as to the amount by which the inductance decreases as the frequency is increased.

The same method has been used to measure the value of small mutual inductances, either by observing the E.M.F. set up in one coil by a known current in the other, or by measuring the self-inductance of the

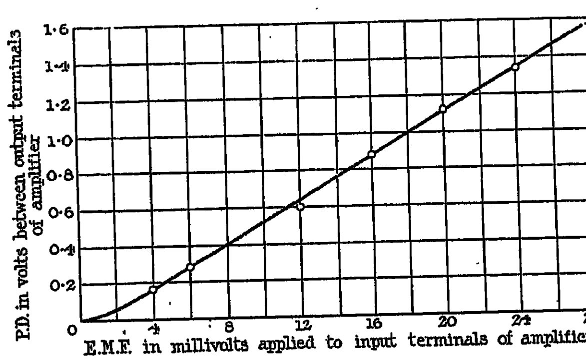

Fig. 15.

two coils joined in series. A mutual inductance of $0\cdot8\,\mu$H has been successfully measured in this manner. The instrument is also useful for measuring the impedance-drop across dynamometer ammeters or current transformers.

(*c*) *Direct measurement of high-frequency resistance.*—The resistance of a conductor can be measured by the same method as that just described for measuring inductance; since the "skin effect" is only appreciable in fairly coarse wires it is necessary to use a considerable length unless a high-frequency current of several amperes is available. This involves a difficulty, for a foot or two of wire must, at high frequencies, have

a reactance comparable with its resistance, and if the length of wire is doubled back on itself to minimize its reactance the axial symmetry of the current distribution will be disturbed.

As an example of the method the resistance of a doubled length of 18 S.W.G. Eureka wire has been measured at various high frequencies. Fig. 13 exhibits the observed values of the ratio R_n/R_0 plotted against the frequency, and Fig. 14 the value of R_n/R_0 plotted against the square of the frequency. The relation between resistance and frequency for this doubled length of 18 S.W.G. wire is given by $R_n/R_0 = 1 + \frac{0 \cdot 131}{10^{10}} n^2$, whereas the theoretical formula for a single length of this size of wire is $R_n/R_0 = 1 + \frac{0 \cdot 16\, n^2}{10^{12}}$. The discrepancy between the observed and theoretical results is no doubt mainly due to the disturbance in the axial symmetry of the current distribution brought about by the close proximity of the return current, a condition of affairs that must exist in all stranded conductors.

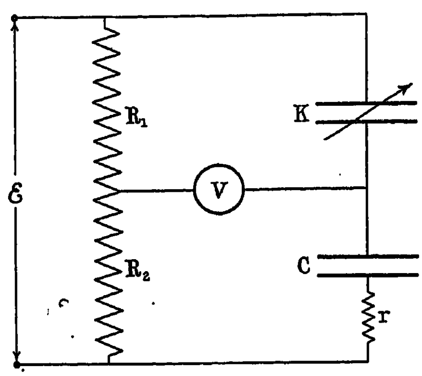

FIG. 16.

(*d*) *Measurement of amplification produced by triode amplifiers.*—The voltmeter is useful in constructing high-frequency amplifiers, for the amplification ratio can be directly measured. The grid type of instrument is most suitable for use with resistance amplifiers, for its reading will not be affected by the large, steady P.D. existing across the anode resistance. Fig. 15 shows the curve connecting input and output voltages (at 10^5 p.p.s.) from a two-stage high-frequency amplifier, the valves used being of the "R" pattern with about 60 V on the anode.

(*e*) *Measurement of signal strengths in wireless telegraphy.**—By interposing a simple two-stage amplifier between the voltmeter and the aerial tuning coil, and without resorting to retro-action in the aerial, signal E.M.F.'s of 300 μV at 3×10^5 p.p.s. have been accurately measured, and signal E.M.F.'s of less than 50 μV have been detected.

(*f*) *Determination of the power factor of condensers.*—The power factor of a condenser can be determined in a very simple manner by using a grid-type voltmeter to measure the P.D. across the diagonal of a condenser bridge. The scheme of connections is shown in Fig. 16, where R_1 and R_2 represent equal non-inductive resistances, and K a variable air condenser which is assumed to have zero power factor. C represents the condenser to be tested, its imperfection being represented by the resistance r; $\mathcal{E}$ is a source of alternating E.M.F. of any required frequency, and V is the thermionic voltmeter.

If the power factor of condenser C is not zero, the P.D. across it will differ slightly in phase from the P.D. across R_2, and, even though K is adjusted so as to be equal in value to C, the voltmeter V will not read zero but a minimum. This minimum reading of V is equal to the vector difference between the P.D. across C and the P.D. across R_2. So long as this vector difference is small compared with $\mathcal{E}$, the ratio $2V/\mathcal{E}$ will measure the angle by which the phase of the current through the condensers departs from the ideal "quadphase" condition, or, in other words, the power factor of the condenser C. For a given reading of the voltmeter V, the smallest angle which can be measured depends simply on the value of $\mathcal{E}$. The smallest value that can be read with an accuracy of 5 per cent is about 0·5 V, so that the smallest measurable angle is about $1/\mathcal{E}$ radians, or, if $\mathcal{E}$ is 300 V, about 12 minutes of arc. The accuracy of the method has been tested by using an air condenser for C and inserting a known resistance for r; under these conditions $r\omega C/2$ should equal $2V/\mathcal{E}$.

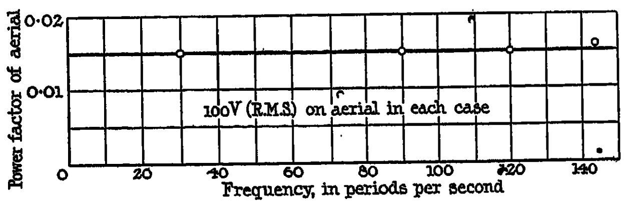

FIG. 17.

As an example of many such tests the following may be quoted for a case where $C = K = 5\,000\,\mu\mu$F, $r = 10\,000$ ohms and the periodicity = 90 p.p.s. The observed values of V and $\mathcal{E}$ were 1·5 V and 212 V respectively, so that $2V/\mathcal{E} = 0 \cdot 0142$, whereas the calculated value of $r\omega C/2 = 0 \cdot 0141$. This method has been used to measure the power factor of an aerial, and incidentally it forms a convenient way of measuring the capacity of an aerial. Fig. 17 exhibits the power factor of the aerial at the Cambridge University Engineering Laboratory at frequencies ranging from 30 p.p.s. up to 150 p.p.s., the voltage on the aerial being 100 V in each case. It may be observed, in passing, that the power factor of the aerial is not entirely independent of the frequency, as Fig. 17 seems to show, but is appreciably different at frequencies of many thousands per second.

(*g*) *Measurement of stray magnetic fluxes.*—The thermionic voltmeter affords an ideal means of mapping stray alternating magnetic fields. The sensitivity of the instrument permits the search coil being of few turns and small linear dimensions, an important consideration where space is very restricted; moreover, as the instrument takes no current, the configurations of the fields to be investigated are not disturbed by the presence of the

* See also E. B. MOULLIN, "Observations on the Field Strength of Horsea Wireless Station," *Journal I.E.E.*, 1922, vol. 61, p. 67.

search coil. It is suggested that the method may be most useful for investigating the stray fluxes in transformers, or zig-zag leakages in induction motors, and other kindred problems.

To illustrate the possibilities of the method some preliminary investigations have been made of the leakage fluxes occurring in a choking coil with a variable air-gap.

The form and dimensions of the choking coil used are shown in Fig. 18. Magnetizing coils of 100 turns each were wound centrally on each limb and occupied a length of 3 inches; the cross-sectional area of the iron was 10·7 cm². Search coils, each having the same number of turns, were wound round the core at the points marked AA′, BB′, CC′ and DD′ respectively. Coil AA′ embraced sensibly all the flux threading the

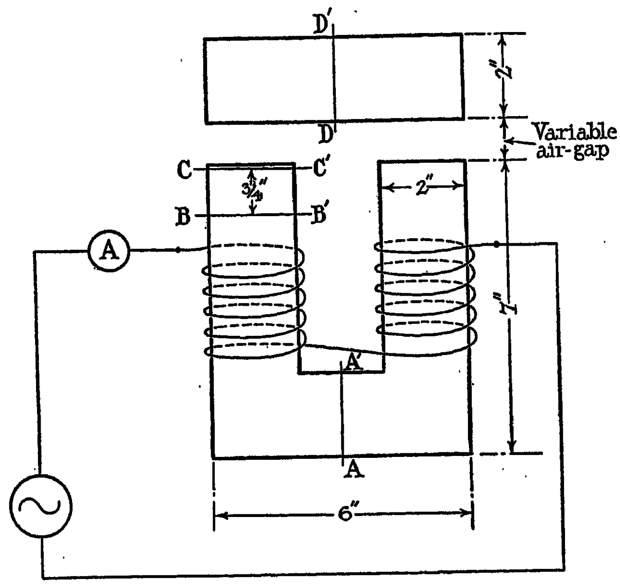

FIG. 18.

magnetizing coils, but would have been more advantageously placed centrally underneath one of the two magnetizing coils. Coil CC′ embraces the flux that issues from the end of the limb, and this is sensibly the same flux that actually crosses the gap and, passing through the head-piece, threads coil DD′. Coil BB placed ¾ inch further down the limb embraces more flux than coil CC′ by the amount which leaves the flanks of the limbs between coils BB′ and CC′. Coils AA′ and CC′, or coils AA′ and BB′, were joined in series but opposing, and the resultant E.M.F. produced in them was measured by the anode-type thermionic voltmeter. The voltmeter reading is consequently proportional to the difference between the fluxes threading the two coils or, in other words, the leakage flux between the two points. Since this leakage flux occurs through paths that are mainly air, it must be sensibly proportional to the current through the magnetizing windings.

Fig. 19 relates to a test of the choking coil at a constant voltage, the current through the windings being altered by varying the length of the air-gap, the mean flux density inside the magnet windings being about 3 000 lines per cm² at time of maximum value. The percentage leakage of flux between AA′ and BB′, also between AA′ and CC′, is plotted against the R.M.S. current through the magnetizing windings. The result is seen in each case to be a straight line, but a line not passing through the origin. The reason why the line departs from the origin is probably because coil AA′ was not situated centrally under one of the magnetizing coils. Had this been the case the E.M.F. generated in coil AA′ would always have been a little greater, and so the difference between coils AA′ and CC′ would have been also a little greater. It will be noticed that the leakage flux appears to become zero when the current is 0·5 A. This is exactly the current taken by the choker with the gap closed up; and in this condition the search coils are situated almost symmetrically with respect to the flux and would therefore have equal E.M.F.'s in them, with or without a small amount of stray flux between them.

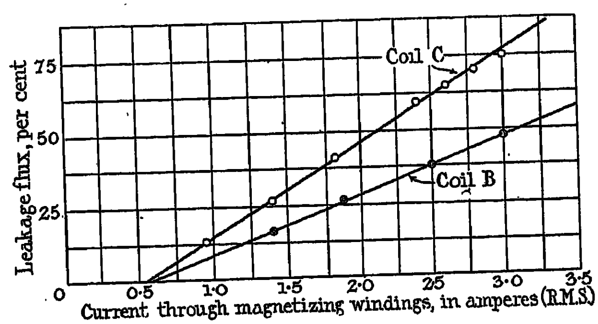

FIG. 19.

(*h*) *Miscellaneous uses.*—If the grid-type instrument is connected across a resistance placed in the field circuit of an alternator, it can be used to measure the extent of the small alternating current superposed on the steady field current, or it may be used to measure the voltage ripples of a d.c. dynamo. Both these applications depend on the fact that it is not cognizant of a steady potential. In this and similar applications it may prove a useful instrument for those who have constantly to diagnose faults in dynamo-electric machinery, and it would often serve to discover a fault that could otherwise have been found only by the help of an oscillograph or other delicate and unportable apparatus.

With the help of an amplifier it may be employed with a thermo-couple to measure the extent of cyclic variations of temperature, such as those occurring in an engine cylinder.

Discussion before the Wireless Section, 6 December, 1922.

Professor C. L. Fortescue: It may well be argued that all the principles involved in this instrument are well known, but it has remained to the author to realize the need for this voltmeter and to produce it in a practical and simple form; and for this he deserves full credit. Of the many applications mentioned in the paper the measurement of high-frequency resistance seems one of the most important, and it is possible that for this purpose the instrument may prove as useful to the wireless engineer as the testing set is to the "heavy" engineer. As a resonance indicator the voltmeter will, no doubt, operate fairly effectively, but this would not appear to be its strong point, and the ordinary "slide-back" method, using a good galvanometer and a strongly negative grid, is far more sensitive. There seems to be some reason to doubt whether the calibration will be permanent. Changes of the grid, filament and vacuum occur in the valves even when run with low filament currents, and only experience of many thousand hours of running will show whether the method of setting the zero will compensate for all these changes. Some degree of screening may also prove necessary when working on very high-frequency circuits.

Major H. P. T. Lefroy: I feel that the instrument described in the paper is probably, at the stage we have now reached in high-frequency engineering, about the most useful one that has been produced for a considerable time, and that its use may lead to improvements in radio apparatus in almost every direction. More particularly, it will enable us to gain a valuable insight into the design of high-frequency conductors and coils, and on various other points which have been difficult to investigate on account of the difficulty of measuring very small high-frequency currents. The instrument is one, moreover, which amateurs can easily obtain, so that, if they wish, they can join in some useful and effective research work. For instance, they are now in a position, with the help of this instrument, to measure signal strength accurately, and to join in the international investigation of signal strength in a way they could not before. In the early part of the paper it seems to me that the author rather suggests that all balance methods are too cumbersome; but in similar work which I have done, using simply a 2-volt accumulator and a 10 000-ohm resistance-box, I was able easily to balance to an accuracy of $0 \cdot 1\ \mu$A, and then to get readings, from signals, up to 1 000 μA, which is a very wide range. I think that high-frequency voltages down to $0 \cdot 01$ volt can thus be measured, simply by putting the accumulator current differentially through the micro-ammeter relative to the anode current. In my experiments I noticed an interesting point, viz. that signals which reduced the anode current by 20 μA were about R9 in the telephone, while those causing a reduction of 500 μA were only R10 or R11, and those about R6 did not cause a reduction of 1 μA.

Dr. E. H. Rayner: There are one or two points which I should like to raise. Has the voltmeter to be calibrated for each particular valve, or is it sufficient to take a given type of valve and substitute one for another? I ask that because for a certain purpose some work has been done recently on valve characteristics, and it was impossible to find two valves with exactly the same characteristics, although they might be of the same manufacture. Another point is this: I notice that the terminals for the connection to the voltmeter are put almost as far apart as possible, but it seems to me that in order to reduce the inductivity of the circuit, with the stray fields which may be present, it would be desirable to bring them closer together, as is usually done in apparatus for very high-frequency work.

Mr. J. Hollingworth: To take a measurement in wireless work often requires far more apparatus than is in use for the whole of the rest of the experiment, and the advantages of a portable instrument are therefore very great indeed. I think we might even go so far as to say that even if the instrument were not found to be an instrument of precision—I do not suggest for one moment that it is not—its value to the alternating-current worker would still be very great. Some time ago when I was trying to use a constant oscillating circuit I adopted the method of always resetting the filament current so as to obtain the same anode current with the same anode voltage, the idea being that it was much more sensitive to anode current, and anode current can be adjusted much more accurately than filament current can be. On calibrating it after three months I found that it had changed 30 per cent. Whether I had a particularly bad valve or not I do not know, but as a result of that I connected up the circuit with a measuring instrument in series, left it on and watched it hour by hour. There were even slight changes during that period, so I think that it will be necessary to make sure that the right point on the anode characteristic is being worked to, unless it can be shown that small variations of the anode characteristic do not produce any appreciable effect. I should like to ask if, by the addition of various resistances in the position occupied by R in Fig. 4, the instrument could be converted into a multi-range apparatus, so extending its uses. I think that the power absorption of the voltmeter varies slightly with the power applied to it; in fact, the apparent resistance of the voltmeter appears to vary slightly with the reading. That, of course, introduces the difficulty that if one is using it on an oscillating circuit, where decrement is of importance, and where the decrement of the voltmeter is comparable with that of the circuit, one does not know the decrement of the circuit until one knows the reading of the voltmeter. If the voltmeter is equivalent to a constant resistance, that will not matter, but if the equivalent resistance of the voltmeter varies with the reading it means recalculating for each reading in order to determine the actual decrement of the circuit.

Mr. F. C. Lunnon: The author's voltmeter is essentially a calibrated apparatus and I think that he rather underestimates the difficulty of obtaining a calibration, for surely it will depend upon the wave-form of the voltages to be measured. I notice that he rather

lightly passes over what has come to be known as the "slide-back" method of measurement. In working under Capt. Round I have used this method for various purposes for a number of years and if it is employed with a knowledge of its error it is sufficiently accurate for most radio measurements. It is essentially not a

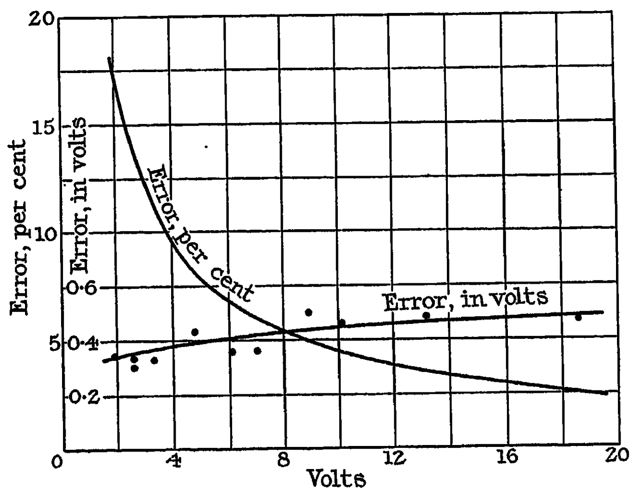

FIG. A.—Curves of error of a V24 valve (No. 21 288). 4 volts across filament; 12 volts on plate.

method for measuring such low voltages as those for which the author's instruments are calibrated, for the reason—which we have always appreciated—that there is a small, constant error inherent to the method, depending on the type of valve used, which would result in too big a percentage error at these small values. About a

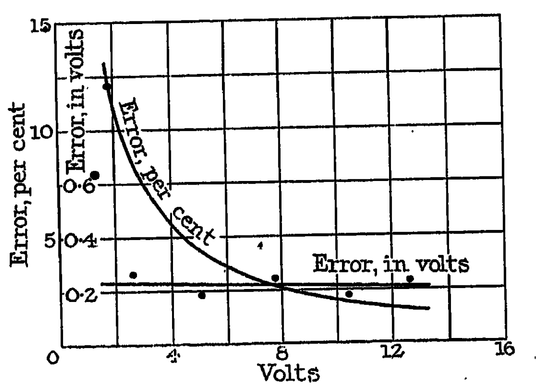

FIG. B.—Curves of error of an S.M. valve (dull emitter) No. 235. 2·18 volts across filament; 7 volts on plate.

year ago I made extensive checks on this method at low frequencies, trying a large number of valves of different types. The result showed that for any particular type of valve the error is practically constant from valve to valve and over a large range of voltage and so, of course, the percentage error decreases as the voltage to be measured increases. For instance, using a M.-O. dull emitter valve the error is 0·2 volt low, which represents a 4 per cent error at 5 volts. A M.-O. V24 valve gives a bigger error, viz. 0·4 volt low. If care is taken to use valves with a good, sharp cut-off—such as a dull emitter—the error will not be greater than 4 per cent for voltages of over 5 volts, and over 10 volts it will be very small indeed. And if, when using a dull emitter, 0·2 volt is added to the readings then,

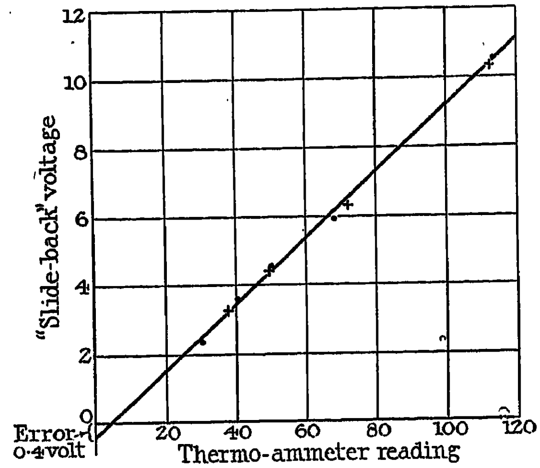

FIG. C.—Test for proportionality between current in an oscillatory circuit and resulting voltage across condenser as measured by the "slide-back" method. V24 valve.

over about 6 volts, the error can be relied upon to be less than 1 per cent. Figs. A and B illustrate these results, and Fig. C and Table A give the results of high-frequency checks which were made three years ago. A point in favour of the "slide-back" method is that

TABLE A.

V24 Valve.

Peak voltage measured by the "slide-back" method across an inductance $L = 1\,460\,\mu$H at $\lambda = 6\,050$ m and compared with the calculated voltage determined from the current I as measured by a thermo-ammeter.

"Slide-back" voltage	Calculated voltage	Percentage error
15·2	15·3	0·655
26·1	26·2	0·38
23·7	24·1	1·66

the very principle by which it operates ensures that no damping can be introduced into the circuit to which it may be connected; and a still greater point in its favour is that it is definitely a measure of peak voltage as against R.M.S. voltage—necessarily doubtful because it depends on wave-form—such as is obtained with the author's voltmeter. He suggested that his voltmeter could be used to measure signal strength by measuring the voltage across an aerial tuning inductance and then calculating the induced E.M.F. in the aerial from a knowledge of the inductance, frequency and resistance of the aerial, and he remarked that this would be a simple method and one that might supersede the present complicated aural method—presumably that

used by the Marconi Company and described by me in the discussion on "Long-distance Wireless Transmission" before this Section in 1921.* This might be so under ideal conditions—with the stations to be measured sending a long dash and in a complete absence of interference from atmospherics or other stations—but it is most certainly not so for practical signal-strength measurement, for example, measuring New Brunswick in England, where the current in the aerial resulting from the E.M.F. induced by the New Brunswick signal is far weaker than the forced current from nearby high-power stations on slightly different wave-lengths, viz. Carnarvon and St. Assise, and far weaker also than the current resulting from atmospherics. And when, in addition, it is remembered that in practice stations send Morse signals and not long dashes it must be obvious that only an aural method, such as that referred to above, can give any results at all.

Major B. Binyon: It is well known that valve filaments are very liable to fracture in transit and, in view of the fact that the calibration of this instrument depends upon the particular valve employed, it would presumably be necessary to return the instrument to the makers for re-calibration in the event of damage to the valve. I should like to ask the author whether he has considered the employment of any special type of valve to overcome these difficulties and whether it would not be possible to employ a valve having a very thick tungsten filament with a current of, say, 3 or 4 amperes or more, which would give an exceedingly long life and not be liable to damage in transit. Since the instrument is not required for continuous use a high filament current would be immaterial.

Mr. R. C. Clinker: I think that anyone who has made alternating-current measurements, particularly measurements of small voltages, will often have felt the need of an instrument such as the author has described. It would be very useful, for instance, in measuring the permeability of iron under a.c. conditions at very low density where a low voltage is induced in a search coil. On page 301 the author mentions the measurement of current by noting the frequency and passing the current through a known inductance. For that, I suggest, it is necessary not only to know the frequency accurately, but also to be sure that the wave is sinusoidal, i.e. that no harmonics are present, which I think is more difficult. I should like to know if the arrangement shown in Fig. 16 would give as good or better results if a variable resistance were put in series with the condenser K and varied until V gave a zero reading. The power factor of the arm containing condenser K would then be known and would be exactly equal to that containing condenser C and resistance r.

Dr. E. V. Appleton (*communicated*): I think that the voltmeter designed by the author (see Fig. 3) will play a great part in the signal measurements of the future. We have had an opportunity of using this type of voltmeter in the Cavendish Laboratory, and have found it quite accurate and very convenient. At first I thought that all the author had done for us was to put a triode in a box, bringing out connections to convenient terminals, but a closer acquaintance with the difficulties of the problem make us admire the way in which he has made the calibration independent of fluctuations of filament-battery voltage. I have been personally interested in two applications of the voltmeter, both relating to the measurement of the strength of continuous-wave signals. For very strong signals, such as are used in measuring the effective heights of aerials, a loop aerial may be used, and the resonance voltage across the condenser may be measured by means of the voltmeter. The insertion of a small, known non-inductive resistance in the coil circuit alters the resonance voltage reading so that from the two values the oscillatory-circuit resistance may be found. The calculation of the signal electromotive force is then a simple matter. In the second method the signal strength is measured by means of the "silent space" which it produces in a simple auto-heterodyne receiver. Thus, if the edge of the "silent space" corresponds to a dis-tuning $\delta\lambda$, where λ is the wave-length, the signal electromotive force E_0 is given by $E_0 = K(\delta\lambda/\lambda)a_0$, where K is a known constant and a_0 is the oscillatory amplitude of the receiver in the absence of signals. Since a_0 may be made of the order of 0·5 volt it is conveniently measured by the author's voltmeter. I know of no other instrument which would be as suitable for such a purpose.

* *Journal I.E.E.*, 1921, vol. 59, p. 677.

Mr. E. B. Moullin (*in reply*): Prof. Fortescue and Mr. Hollingworth have suggested that the calibration may not remain permanent over a long duration of time, but whether this will prove to be the case or not experience alone can show. If the filament voltage is kept down to 3·6 V I hope and expect that no appreciable ageing will take place. I have had one of these instruments in constant use for about 8 months and no change has so far taken place in the calibration: it is extremely easy to make a low-frequency check of the calibration, and until long experience has been gained it may be as well to check the instrument every 6 months or so. It is possible that ageing effects would be equivalent to a very small change in filament potential, and experiment shows that such small changes affect only the zero and not the law of the scale. Hence if ageing does take place it is quite possible that the instrument can be corrected by slightly setting up the pointer zero without making any alterations in the scale.

Prof. Fortescue and Major Lefroy have referred to the use of the instrument for measuring high-frequency resistances. I have used it a great deal for measuring aerial resistances and coil resistances by employing it as a current indicator, while the E.M.F. introduced into the circuit was measured by a potentiometer slide-wire.

In reply to Dr. Rayner each instrument has to be calibrated with its own particular valve, but in the case of the grid instrument different valves by the same manufacturer seem to repeat themselves within 5 per cent.

As Major Binyon suggests, it may well be advantageous to use a thick filament and so avoid all risk of damage in transit: this might also permit of a slightly less sensitive galvanometer being employed.

I am afraid that the amount of scale control obtainable by altering the anode-circuit resistance is not sufficient to provide a multi-ranging device, but no doubt a

considerable extension of scale could be provided in this manner.

The method of calculating the effective resistance of the voltmeter at any reading is set out in the paper, and I think that the example given at the end of Section 4 is a fair one for the purpose of showing that there are few cases where the decrement will be of importance. If cases arise where the decrement is important it is only necessary to tap the voltmeter across a portion instead of the whole of the inductance, and thereby reduce the decrement introduced; this, of course, means an increase in the power supplied to the circuit, but the sensitivity of the instrument when used as a current indicator is so great that this is of no practical inconvenience.

Mr. Clinker's suggestion of placing an extra resistance in the condenser arm of the bridge and so producing a balance would usually be an improvement: with very small condensers and low frequencies this added resistance would have an inconveniently high value.

I agree with Mr. Lunnon that the calibration must be to some extent dependent on wave-form, but to what extent has not so far been investigated. In high-frequency work where one is usually working with highly inductive circuits of low decrement tuned to resonance it does not seem possible that one can get harmonics in the current that are comparable with the fundamental, hence I think that no anxiety as to wave-form need be felt in high-frequency work. I do not see how the slide-back method is any better in this respect, for the peak voltage which it measures is also dependent on wave-form. Also, a reference to my analysis of the accuracy of the slide-back method which recently appeared in the *Wireless World* (1922, vol. 10, p. 1) will, I think, show that Mr. Lunnon's constant correction of about 0·4 V will depend very much on the wave-form. I think he will agree that if the wave had a dimple in the top, and, therefore, two peaks, the constant correction would be much less than 0·4 V, and that if it had a very sharp peak instead of a dimple, the constant correction would be much more than 0·4 V. Another disadvantage that the slide-back method appears to possess is that not only is it necessary to add a rather uncertain correction but there must also be some uncertainty in deciding on the appropriate slide-back. That this uncertainty does exist is clearly shown in Mr. Lunnon's curves, in which the observation points are scattered above and below the line. Above, say, 15 V the method may no doubt be taken as correct, but this makes the slide-back 10 times as insensitive as the instrument described in the paper.

The aural-comparison method to which I referred was the method described by Prof. Vallauri and is probably similar to that used by Mr. Lunnon. I have used the voltmeter a good deal for measuring signal strengths, and according to the Austin-Cohen formula it is quite possible to measure transatlantic signals by the method indicated in the paper and recently described more fully in the *Journal*.*

* *Journal I.E.E.*, 1922, vol. 61, p. 67.

DISCUSSION ON
"OBSERVATIONS OF THE FIELD STRENGTH OF HORSEA WIRELESS STATION." *

Mr. J. Hollingworth (*communicated*): The experiments and results given in the paper are very interesting to those who are engaged on this problem of measurement. It is to be noted that the author confirms the present general tendency to avoid the use of an audible system wherever possible, though there may occasionally be cases in which it is preferable. A certain number of measurements were made at the National Physical Laboratory on this transmission, but their object was largely to investigate a new system of measurement. Time did not allow of this being calibrated before the tests commenced, so that readings were discontinued after a time in order that it might be done, with a result that on no occasion did the date of Mr. Moullin's tests coincide with those at the N.P.L., so that direct comparison is not possible. I should like to express my absolute agreement with the author where he emphasizes the necessity of check measurements. In such an indirect process as a measurement of this type the possibilities of something going wrong are so great that it is very difficult to place entire reliance on a single reading unsupported by any internal evidence. With regard to details of the system, the discrepancies in the results obtained with the different mutual inductances are very likely due to a small capacity coupling. Personally, when using a similar system I never rely on a calculated value, but proceed as follows: The larger mutual inductances can be measured directly by passing a rather larger current at the given frequency through the primary and connecting a Duddell thermo-galvanometer across the secondary. Provided one is not working near the natural wave-length of either coil, the mutual inductance can be calculated from these figures and the low-frequency inductance of the secondary. This process breaks down for the smaller values of mutual inductance, but by measuring the same signal with different pairs of mutual inductances a ratio $M_1 : M_2 : M_3 \ldots$ can be obtained. I have found that over the range in which both methods of measurement are possible the ratios obtained by the two methods are almost invariably within 1 per cent of one another, and so I have no hesitation in accepting the ratio obtained by the second method for mutual inductances which are too small to be measured by the first. Hence, if the absolute value of the largest mutual inductance can be measured by some direct method, the values of all the others can be found. There appears to be considerable difference of opinion over the meaning of the effective height of an aerial as used in the formula

$$E = \frac{K\pi h_s I_s}{\lambda d}$$

At the Paris Conference, 1921, it was suggested that it should be defined as the height of the equivalent half dipole, and the constant K is then 120. It was also suggested that, as a first approximation, the effective height should be taken as 0·55 of the mechanical height; and in the *Radio Review* of April 1921 Prof. Vallauri gives this ratio for the Rome aerial under certain conditions as 0·64. Hence in Mr. Moullin's formula where $K = 60$ is used, it appears as if his value of the effective height should at times exceed the actual height, which appears to contradict his remarks in the second column of page 72. As a matter of fact, in the N.P.L. measurements K was taken as 120 and h_s as 100 (this value being assumed, as the correct value was unknown). The results on the 2 500-m signals mostly came out about 10 to 20 per cent in excess of the theoretical value, neglecting absorption. It appears, therefore, that if the correct value for h_s had been used, the results would have shown the absorption between Horsea and the N.P.L. to be negligible.

Mr. E. B. Moullin (*in reply*): I agree with Mr. Hollingworth that it is very advisable to make an actual measurement of the mutual inductances, but, as mentioned in the paper, adequate means for doing so were not at my disposal. Personally, I much prefer to measure the local E.M.F. by means of a resistance potentiometer, because by so doing it is much more easy to make calibration curves of the type shown in Figs. 7 and 8. If the resistances are made of short lengths of fine wire doubled back on themselves I think that there is no need to fear that the potentiometer has a reactance comparable with its resistance, at any rate for frequencies less than 10^5 periods per second. In any case, as the reactive drop is at right angles to the resistance drop it can have an appreciable value and still make only a second-order change in the total drop.

I am glad that Mr. Hollingworth has called attention to the discrepancy that exists in defining the effective height from the formula $E = K\pi h_s I_s/\lambda d$, for it seems to me that this discrepancy is bound to lead to confusion in the future; it seems common to find K taken as 60, and equally common to find it taken as 120. Now it seems to me to matter very little which value of the constant is taken so long as everyone takes the same. Would it not be a good thing to have some definite ruling on this point, together with some rules as to the manner in which the effective height is to be measured? If this were done then we should know that all values quoted for the effective height of an aerial were defined and measured in a standard way.

With regard to the effective receiving height measured as described on page 72, surely this method of measurement is independent of the value of the constant discussed above. The value of the field strength produced by a distant station is first measured by means of a loop, and it is then found that the same field produces a certain E.M.F. in an aerial. In the case of an aerial where capacity is sensibly all concentrated in the roof, the value of the E.M.F. divided by the field strength must surely give the effective receiving height. In the particular case considered, the curve showing the current distribution in the up lead proves that the capacity was concentrated in the roof.

* Paper by Mr. E. B. Moullin (see page 67).

INTRODUCTORY NOTES TO A LECTURE ON "VARIABLE-SPEED ALTERNATING-CURRENT MOTORS WITHOUT COMMUTATORS."

By F. Creedy, Associate Member.

(*MS. first received* 23*rd November*, 1922, *and in final form* 7*th March*, 1923; *lecture delivered before* The Institution 4*th January, before the* North Midland Centre 9*th January, before the* South Midland Centre 10*th January, and before the* North-Eastern Centre 22*nd January*, 1923.)

Summary.

After a short general discussion, a new method of pole-changing, involving the use of a number of phases greater than that in the line, is explained, together with means for simplifying the connections :—

(A) By the use of mutually reversed coils.

(B) By a star-mesh connection.

The phase transformer needed to produce the increased number of phases is next described, and it is shown that the current in the windings intermediate between the three-phase tapping points is reduced to a very low value as in the rotary converter, making the apparatus small and inexpensive.

The switchgear employed is next discussed, and it is pointed out that the methods described render the squirrel-cage motor adaptable to almost all purposes, since they enable it to give good starting torque with low current.

Machines with slip-ring characteristics are also described and test-results discussed.

A description is given of the cascade motor, and its unique characteristic of giving gradual adjustment between speeds is explained. Two-, three- and four-speed motors having this characteristic are referred to.

Some tests of large rolling-mill and other motors are given and finally a description of the application of the cascade motor as a short-circuit motor machine with slip-ring characteristics, and as a unity-power-factor synchronous machine of greater simplicity and less cost than any other type.

Introduction.

It has become sufficiently clear during the past few years that the polyphase alternating-current system will ultimately be universally adopted for power supply on a large scale. One of the chief difficulties at present existing with this system relates to the provision of a satisfactory variable-speed motor, capable, if possible, of operating on high-tension polyphase currents without the necessity for the transformation of the whole of the power. The solution of this problem is very far from being an easy one and, in fact, it is only in comparatively recent years that satisfactory progress has been made.

In the first place, the different applications for a variable-speed motor vary very widely among themselves, and it is by no means likely that a single type of motor is best adapted to meet the whole of these different forms of application.

It will be desirable first of all, therefore, to consider rather more in detail what is the real nature of the problem of producing a satisfactory variable-speed alternating-current motor to meet every kind of practical condition.

The Problem of Variable-speed Alternating-current Motors.

There are, in fact, a considerable number of different classes of variable-speed service.

These may be more or less accurately summarized as follows :—

(1) *Speed-range.*—All practical applications, with very few exceptions, can be covered by a motor having a speed-range of 3—1. Other speed-ranges in wide demand are 2—1 and 1·5—1. It would, of course, be desirable, if compatible with the other conditions of the problem, to have a machine capable of gradual speed-variation from one end to the other of any of these ranges without continuous loss of power at any speed. If this should not prove possible, and it becomes necessary to use a number of speed steps, these should be fairly numerous, say not less than 4 to 6, in a speed-range of 3—1.

(2) *Starting.*—In certain cases, e.g. the compressor drive, the printing press or the reciprocating pump, variable-speed motors must be capable of starting with a very high torque, while others, e.g. machine tools and fans, require only a moderate starting torque, hence provision must be made for both these cases.

(3) *Speed changing.*—In certain cases, e.g. machine tools, printing press drives, compressors, lifts and cranes, etc., the speed has to be changed while running; while again in others, e.g. mine fans, pumps, calenders and merchant mills, the speed is only changed occasionally in changing operations, though here, of course, the speed-variation required in order to render the use of a flywheel possible is not referred to, but merely that required to enable the mill to deal with different classes of work.

In these cases there is no serious objection to shutting the machine down and re-starting, and where this is possible the problem is simplified to a considerable extent.

Where the change of speeds is in steps, care must be taken that the change from one step to the next is effected without a serious shock to the system, either mechanical or electrical.

(4) The first cost of the equipment, as well as the cost of attendance and upkeep, must be moderate. Repairs must be capable of being carried out without difficulty.

(5) The efficiency of the equipment should be as

high as possible, since high efficiency over a large range of speeds is the chief object of installing a variable-speed alternating-current motor. A low consumption of wattless current is also desirable.

(6) For the vast majority of applications the motor should be capable of giving a constant torque at all speeds or a horse-power proportional to the speed. For a certain class of machine tools, however, a constant horse-power characteristic is desirable.

The object of speed-variation in the driving of machine tools is to enable a cut to be taken on different diameters at the same peripheral speed, objects of large diameters being driven at a low speed (r.p.m.), and objects of a small diameter at a higher speed. Where, as in lathes, modern drilling machines, milling machines, etc., the amount of energy dissipated in friction is small and most of the power of the drive is actually devoted to cutting, this means that approximately the same horse-power is taken by the tool at no matter what speed it operates.

There is, however, another class of tool in which the size and weight of the tool is determined chiefly by the necessity of rigidity, e.g. large boring mills, planers, etc. In this case the greater part of the energy supplied to the tool is devoted to the moving of heavy masses and is ultimately dissipated in friction. In this case the tool requires a constant torque and an amount of power in proportion to the speed.

Difficulties in Designing a Satisfactory Variable-speed Alternating-current Motor.

The most obvious way to produce such a motor is to make the closest possible imitation of the direct-current machine, and it has long ago been shown that numerous types of single-phase and polyphase commutator machines having, in theory, characteristics resembling very closely those of the direct-current machine are possible. These commutator machines have never been more clearly described than in a lecture * given by Dr. S. P. Smith, but it is indisputable that the present wide utilization of electric power supply is due very largely to the simplicity and robustness of the polyphase induction motor and I have always thought it a disastrous mistake to abandon the induction motor without examining whether some system of control cannot be worked out so as to enable it to carry out satisfactorily without any fundamental alteration variable-speed requirements.

Every variable-speed application should, in my opinion, be considered on its merits. In some cases a commutator machine is undoubtedly the right apparatus to use. Its advantages are the greatest:

(1) On constant-speed work where it is possible to keep the size of the commutator and the amount of brushgear within reasonable limits by appropriate design.

(2) On very low-frequency circuits where similar possibilities exist.

(3) Where there is an imperative demand for a continuously adjustable speed justifying all the sacrifices in other directions which must be endured in order to attain it. These cases are, however, in my opinion, relatively few. Assume, for instance, that we wish to drive a boring mill by means of a variable-speed alternating-current motor, the best speed of the table for a particular class of work being 20 r.p.m. With a speed control by steps it may be impossible to get exactly this speed, speeds of 19 r.p.m. or 21 r.p.m. being the nearest available, and I feel that this difference is not worth considering in most cases.

* *Journal I.E.E.*, 1922, vol. 60, p. 308.

Confining ourselves therefore to methods of controlling the induction motor so as to obtain variable-speed shunt characteristics, we find that its natural lines of development are two in number :—

(1) Speed change by changing the number of poles.

(2) Speed change by cascade operation.

Both these methods lead to extremely useful types of apparatus and I propose to discuss each in turn.

Part 1.

Speed Change by changing the Number of Poles.

Without ignoring the work of early inventors, such as Dahlander, Lindström and Alexanderson, who have provided means of adapting a single winding to give, for instance, two numbers of poles having a fixed ratio, it is not unfair to say that the idea of using the method of pole changing to produce a machine having anything resembling a gradual variation of speed by

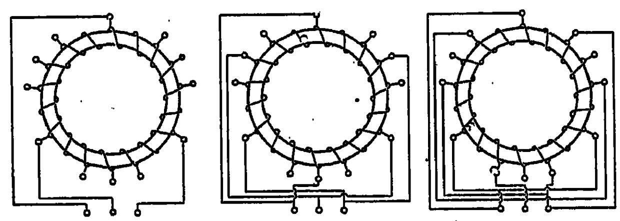

Fig. 1.

small steps between wide limits, would have been regarded a few years ago as chimerical. Yet it is also obvious that if by any means we could render practically available all the numbers of poles which exist within a given range, we have a machine with a very high degree of practical usefulness. For instance, on 50 periods between the speeds of 375 r.p.m. and 1 000 r.p.m. there are six numbers of poles available.

As the methods by which all these numbers of poles are rendered practically available have not yet been publicly described, I propose to dwell on them at somewhat greater length than is devoted to the methods of speed-variation previously described.

One method by which all these numbers of poles might theoretically be rendered available with a single winding has long been known, i.e. the use of a ring winding tapped at the various points necessary to give different numbers of poles, as shown in Fig. 1. It is well known that a ring winding can be used on any number of poles, if a number of equidistant tappings equal to three times the number of pairs of poles are brought out on each speed, equalizer connections being made between tappings 1 to 4 throughout the circumference. To obtain

six numbers of poles from the same winding in this way, however, would require a formidable number of tappings, and to connect them together in the various manners required would involve an equally formidable type of switchgear.

In addition to this, the ring-wound machine is highly inconvenient from a manufacturing standpoint, though practically equivalent results could, in fact, be obtained from a lap-wound drum winding.

A further difficulty arises from the fact that the voltage induced in any section of the machine consisting of, say, two, three or more coils connected in series having a given number of turns is proportional to the rate at which the magnetic lines cut the conductors, and this rate is, of course, proportional to the speed of the flux wave, which is practically the same as that of the revolving element. Consequently, at the highest speed of the motor, the flux wave is cutting the conductors at a very high rate and, if the E.M.F.

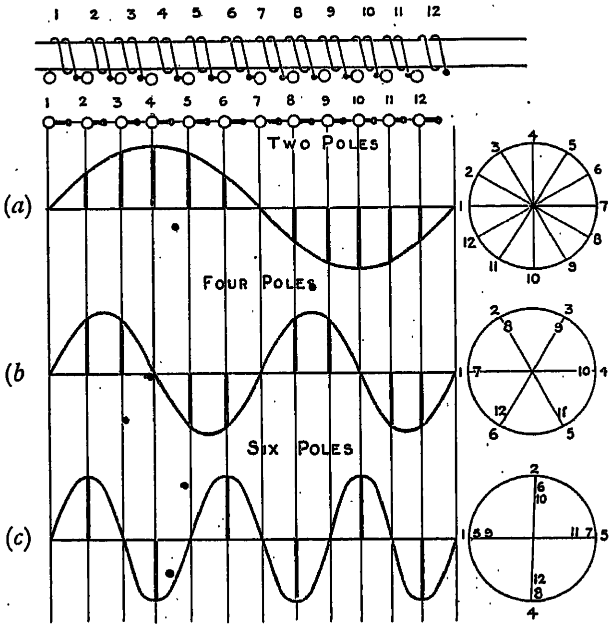

FIG. 2.

applied to any section is fixed, only a small flux will be required to produce it, owing to the high rate of cutting.

On the low speed of the motor, on the contrary, the flux wave is cutting the conductors at a low rate and, consequently, if the E.M.F. across the sections remains the same as before, a large flux will be necessary to produce it.

Hence, the flux of the motor will tend automatically to fall off in proportion to the rise of the speed in much the same way as it does in the direct-current motor, and hence such a motor having a constant voltage per section will tend to have a constant horse-power characteristic, which is not at all what is demanded in practice.

Means must therefore be provided to increase the voltage across each section more or less in proportion to the speed. These difficulties may be summarized as follows:—

(1) The difficulty of producing a winding having a moderate number of terminals and capable of simple switching.

(2) The difficulty of varying the voltage across a section containing a fixed number of turns, so as to keep the flux approximately constant with increasing speed without the use of costly apparatus.

Method of overcoming these difficulties.—The solution to all these difficulties was only found gradually. In order to overcome the necessity for a very large number of terminals, a method of pole changing entirely different

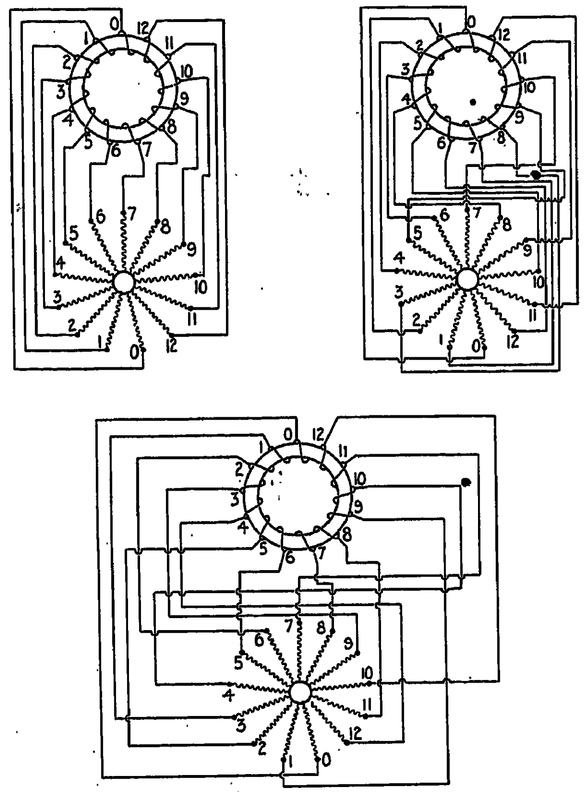

FIG. 3.

from that described above was adopted. This method is shown in Figs. 2 and 3. Still considering a ring-wound machine, assume it to be divided into 12 sections, shown developed in Fig. 2.

At this point it may be convenient to describe a diagrammatic method of denoting the windings of alternating-current machines which I have developed in order to simplify winding diagrams. It will be seen that the ring winding shown at the top of Fig. 2 is divided into 12 sections, each section being shown as consisting of two turns. The beginning of each section is denoted by a white circle and the end by a smaller blackened circle, the extremities of the various sections being connected in series in the usual manner. An obvious simplification for diagrammatic purposes is to omit the drawing of the winding and merely retain the two terminals of each section, joining them by a straight

line in order to show that they belong to the same section. This diagrammatic method of denoting the winding is shown immediately below the drawing of the ring in Fig. 2, the sections being numbered in order round the circumference, and the method is made considerable use of in these notes.

Imagine the 12 sections of the ring winding shown in Fig. 2 to be carrying currents differing in phase from one another by 60°, the current vectors being shown on the right of Fig. 2 (*b*), the current in section 1 having a phase 0°, that in section 2 having a phase 60°, that in section 3, 120°, and so on. These vectors when projected on a vertical axis in the usual way give, of course, the instantaneous currents in the different sections, which may be plotted as shown on the left of Fig. 2 (*b*). We thus obtain a series of ordinates the extremities of which lie on a sine curve, having two positive and two negative maxima, i.e. four poles on the circumference. If, however, we so reconnect these sections that the phase difference between adjacent sections is 30° and plot out the ordinates as in Fig. 2 (*a*), we obtain another sine curve having one positive and one negative maximum, i.e. two poles, while if we make the phase difference between the sections 90°, as in Fig. 2 (*c*), we obtain a curve having three positive and three negative maxima, i.e. six poles.

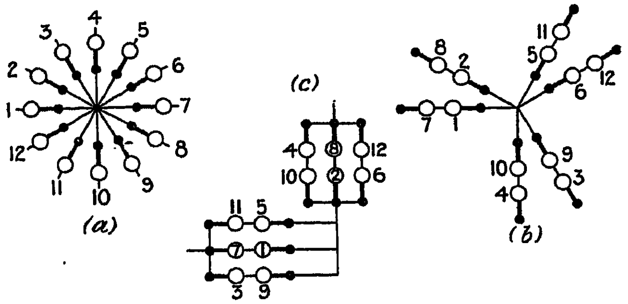

FIG. 4.

In Fig. 3 are shown the connections whereby this change of phases may be accomplished for the case of 13 phases, which is practically more convenient in some respects. As will be seen, it involves the use of 13 terminals on the motor (still shown as a ring winding) and some means of producing a number of phases (viz. 13) equal to the number of sections in the motor winding. Since thirteen-phase distribution is never used, this involves some means of converting from the usual three-phase supply to the number of phases required by the motor and a new piece of apparatus, the phase transformer or converter, is required with this method of control.

When we realize that this method of control involves a phase converter, it may appear as if we had merely simplified the switching by introducing another piece of apparatus which will cost as much as the switchgear with which we have dispensed.

It will be shown later, however, that this is far from being the case. The construction of this phase transformer with a suitable degree of simplicity involves problems of its own, particularly where a large number of phases are required. The method of solving these problems will be described at a later stage.

Although the simple method of pole changing just described was sufficiently encouraging to justify the construction of one or two machines for special purposes, it was not found sufficiently simple to be the final solution of the problem. Experience showed that even the number of terminals possessed by such a motor was too great in practice if a large number of speeds, e.g. five or six, was aimed at. In this case the number of terminals is not less than 30, which was found to be not a practical number, and still further means of simplification were therefore sought.

It was found possible to reduce the required number of terminals in several ways. It is clear, first, that wherever we have currents differing 180° in phase, that is to say, mutually reversed, it is not necessary to supply two distinct phase-transformer terminals to obtain these two phases. If the two sections are connected in series or parallel, mutually reversed, they can be supplied from a single terminal.

For instance, returning to Fig. 2, if we wish to connect the motor only for two poles and six poles we find that in both these cases sections 1 and 7, 2 and 8, etc.,

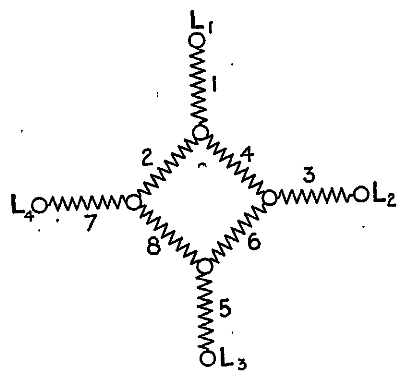

FIG. 5.

are diametrically opposite in phase. We may therefore connect them in series reversed as shown in Fig. 4 (*b*), in which the sections are denoted by the diagrammatic method already described and the direction of the straight line joining the two extremities is made to represent the phase of the current in the section.

Connecting all the sections in star, we require 12 terminals to give two poles. Connecting opposite sections in series reversed we require only six, although if we compare Figs. 4 (*a*) and 4 (*b*), we see that each section in the latter is parallel to the same section in the former, i.e. it carries current of the same phase.

The same connection (viz. diametrically opposite sections connected in series reversed) is also available on six poles, and the diagram for this is shown in Fig. 4 (*c*). Hence, we see how by making use of this simple device we may materially reduce both the amount of switching and the number of terminals required on the phase transformer.

A second method of reducing the number of terminals consists in putting alternate sections of the winding in mesh and the remainder in star, the mesh being

connected in the centre of the star as shown in Fig. 5, for the case of 8 sections and 4 phases.

It will be seen from this figure that the mesh sections are intermediate in phase between the star sections, e.g. section 2 is intermediate in phase between sections 1 and 3, and so on, thus, although the winding connected as in Fig. 5 requires only four terminals, the E.M.F.'s across the various sections are nevertheless in eight distinct phases.

Again, it was found in most cases that while this method of connection might suffice to double the number of phases on a particular number of poles, yet in order to produce the same result on another number, the whole or many of the sections must be disconnected from one another and reconnected in a different order. Thus it would seem that we have only simplified the transformation in order to complicate the switching.

The method of reversal and the star-mesh method may be combined, and thus we may obtain windings in which the E.M.F. across the sections has four times as many phases as that supplied to the terminals.

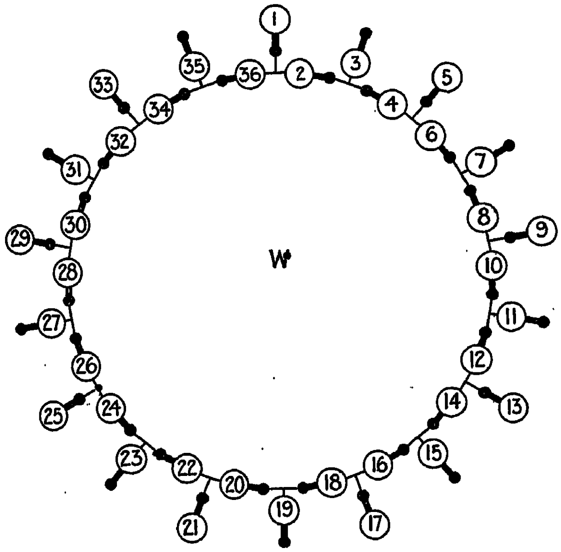

FIG. 6.

After a very large amount of research, extending over a considerable period of time, a winding was found in which this result could be accomplished, not on one number of poles only, but over a large series of numbers covering a speed range of 3—1 or more, without reconnecting the winding in any way when changing the numbers of poles. This winding is shown in Fig. 6 for the case of 36 sections, 18 of which are connected in mesh and an equal number connected in star to the angles of the mesh, alternate sections in the mesh being mutually reversed and alternate sections in the star being also mutually reversed, the mesh sections alternating with the star sections around the circumference of the machine.

The winding shown in Fig. 6 (containing only 18 terminals) can be, and is being, frequently used on all numbers of poles from 6 to 16 and is, with a slight further modification, also capable of being used on further numbers of poles from 20 to 26.

This connection, therefore, gives us not only a winding of a very simple character with a moderate number of terminals (18) capable of reconnection in a simple manner for a large number of different numbers of poles, but it also gives us the characteristic which was shown above to be desirable, viz. that of having an approximately constant flux on all numbers of poles. It is difficult to explain the cause of this in a simple manner, but one may say briefly that it is due to the fact that the number of sections in series between terminals having a given phase difference of, say, 120°, becomes gradually greater and greater as we increase the number of poles, or decrease the speed, so that as the rate of rotation of the flux wave gets less and less, due to the decreasing speed of the motor, the voltage across any section having a given number of turns also becomes less and less approximately in the same proportion, and thus about the same flux is needed to balance this voltage at all speeds.

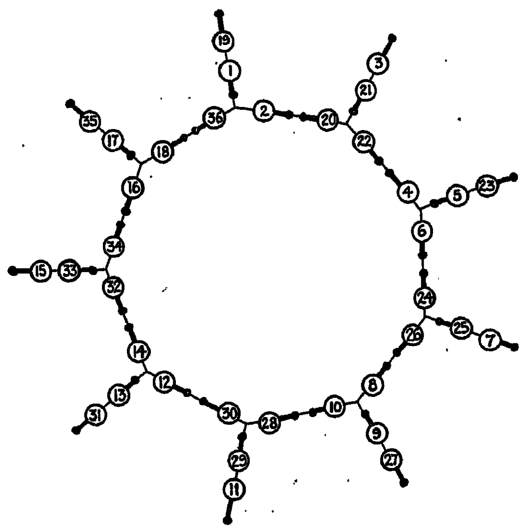

FIG. 7.

A further simplification is possible where, for instance, only odd numbers of pairs of poles are required and, consequently, diametrically opposite sections are always opposite in phase on every number of poles which a machine is required to give, and, therefore, may be permanently connected in series, mutually reversed.

The winding of such a machine is shown in Fig. 7 and, as will be seen, has only 9 terminals, capable of operating on 2, 6, 10 and 14 poles, and, with a slight further modification, on 22 and 26 poles. This winding is, I believe, the simplest known multi-speed winding. It requires no more than 9 phases, while the original winding may require 18 phases.

THE PHASE CONVERTER.

Having described how the difficulties connected with designing a multi-speed winding have been overcome by means involving the use of a phase transformer or converter, it will next be desirable to describe how this

apparatus is constructed in practice. In certain cases, e.g. where a single motor is operated from a generator which serves no other purpose, as in ship propulsion, no such transformer is needed, as there is no difficulty in winding the generator for the number of phases required, but in the majority of cases the machine, if it is to be of any practical use whatever, must operate from a power supply having, say, not more than three phases, and hence it is of vital importance to the practical success of the apparatus that this phase transformer should be not merely technically satisfactory, but should also be capable of being built at a very moderate price.

By restricting the number of phases to multiples of three, the transformers to be excited from a three-phase circuit may be simplified very materially, and it will be convenient to describe the transformer as used in connection with the winding previously referred to. This transformer does not differ externally in any way from the standard three-phase core-type transformer, built in the usual way with three exactly similar limbs. The connections, however, are as shown in Fig. 8, in which all the windings shown by lines parallel to one another are considered to be wound on the same limb of the transformer. Since the windings shown

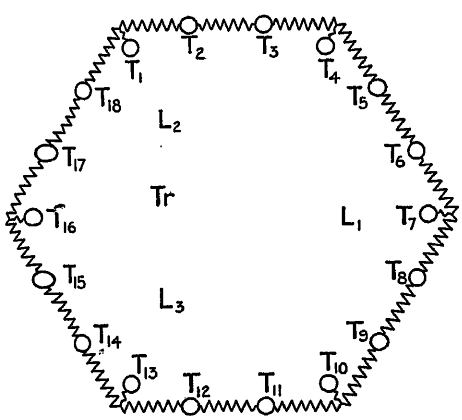

FIG. 8.

in this figure are drawn parallel to three straight lines at 120°, it follows that only three such limbs are needed.

If we take a three-phase transformer having two secondary sections on each limb, and connect these sections in the manner shown, which may be called a hexagon connection, we obtain an apparatus from which six-phase currents may be derived by bringing out terminals from the corners of the hexagon. If, however, we tap the sides of the hexagon in the manner shown, winding on the three limbs, in addition, six small, auxiliary sections to be connected to the corners of the hexagon, it is possible without further elaboration to obtain no less than 18 phases, as has been amply proved in practice, the tappings shown in the diagram lying in a circle.

So far, we have regarded the hexagon winding with tappings as being the secondary, and have assumed that there is a primary winding which carries the three-phase currents. But if no voltage transformation is needed, as in this case, a separate primary is not needed, for the primary terminals may be connected direct to alternate corners of the hexagon, or even, in order to save extra terminals, to the extremities L_1, L_2, L_3 of three of the small, auxiliary sections wound on the transformer and corresponding to the secondary terminals T_1, T_7, T_{13}. This latter plan is adopted to avoid the necessity of bringing out three extra primary terminals.

By using the apparatus as an auto-transformer in this way we at once abolish the whole of the primary windings and, therefore, reduce the amount of copper on the transformer to half, or, in other words, double the rating of a transformer of a given size.

We do more than this, in fact, because the primary and secondary currents flowing in opposite directions in the same windings give a resultant which is very materially less than the secondary current alone. This is exemplified in Fig. 9, which shows the currents in the sections of the 30-phase transformer, which formed part of the original experimental machine which was constructed to test the present method of speed-variation in its earliest form, L_1, L_2 being the three-phase terminals.

It will be seen that the current in the neighbourhood

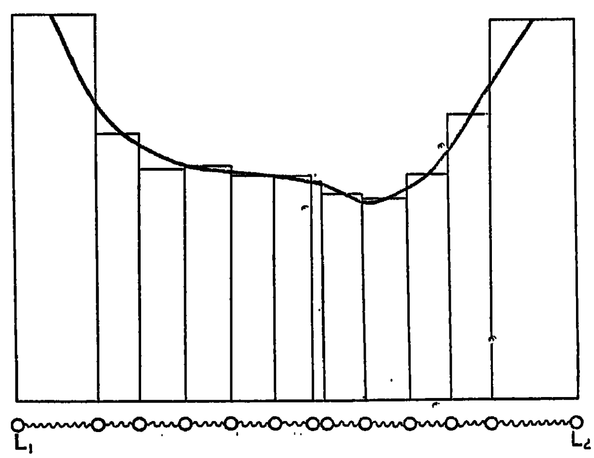

FIG. 9.

of the three-phase terminals is much greater than at points intermediate between them, and, in fact, falls off to less than one-half at a point midway between the terminals.

Fig. 10 shows a similar curve for up-to-date 9-phase and 18-phase transformers as now being constructed commercially by the Metropolitan-Vickers Electric Company for use with these machines. The same reduction in current per section at a point intermediate between the three-phase terminals T_1, T_7 is noticed here, and the analogy between the reduction of current in these transformers and the similar reduction which takes place in the armature of a rotary converter in sections intermediate between the tapping points may be referred to.*

As a result of this further reduction a phase transformer to transform a given amount of power, say from 3 to 9 or 18 phases, will require a size of transformer of only between 30 to 40 per cent of the rating of the trans-

* I hope to publish the full theory of these phase converters on another occasion.

former which will be required to convert the same amount of power, say from one voltage to another.

Still another economy which has the effect of still further reducing their capacity can be effected in the

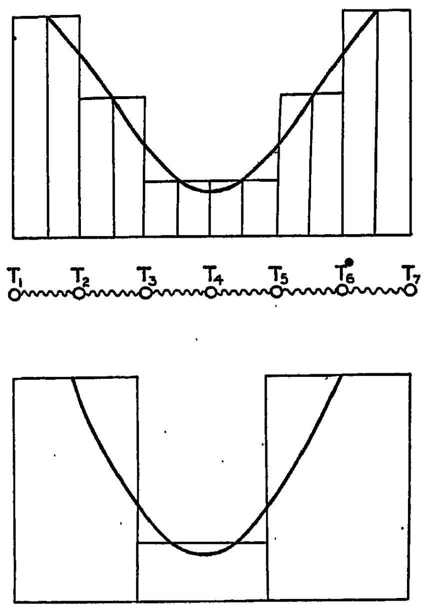

FIG. 10.

use of these phase converters. In a constant-torque motor giving a horse-power proportional to the speed, the amount of power taken will also be approximately proportional to the speed. For instance, the power not being used on that speed but coming into operation for the first time only at 750 r.p.m., we shall be able to reduce its capacity to 0·75 times the value which would be needed to supply the power required at 1 000 r.p.m., making it only 22 to 30 per cent of the capacity required to transform the whole power. By way of analogy to this plan, we may refer to an automobile gear box in which it is usual to give direct drive on the top speed, thereby reducing the amount of power to be transmitted by the gears. The above is the electrical form of the direct drive.

With speeds of 1 000 and 600 r.p.m. the rating of such a transformer may be only from 18 to 22 per cent of the transformer rating needed to handle the maximum power taken by the motor at top speed. It forms, therefore, by no means an expensive item in the equipment, much less so, in fact, than the transformer required with many types of variable-speed commutator motor, the capacity of which is proportional to the difference between the speed of the machines and synchronous speed.

The controller.—The only part of the equipment still to be described is the controller needed to effect the changes of connection between the phase transformer and the motor.

Different types of controller are, of course, required for different speed combinations. It is very easy to obtain combinations giving rise to very complicated circuits, but if care is taken to use the speed combinations best adapted to known types of winding and to choose the types of winding best adapted for the speeds required, the following rule for three-phase circuits may be enunciated :—

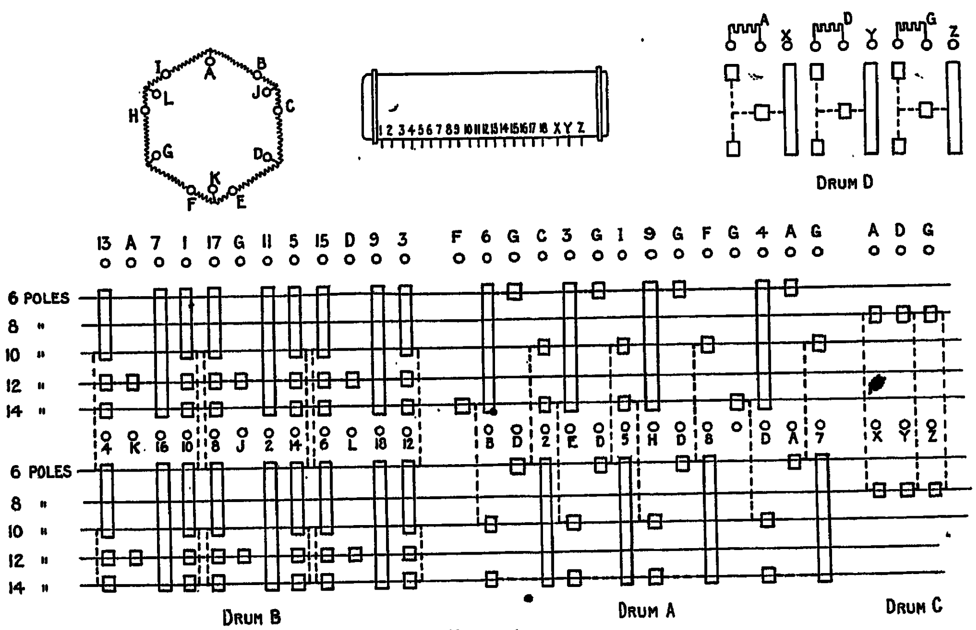

FIG. 11.

taken at 750 r.p.m. will be only 0·75 times the power taken at 1 000 r.p.m., and if we can arrange the winding of our motor so that it is directly connected to the line when operating at 1 000 r.p.m., the phase converter

A three-phase multi-speed motor for any number of speeds up to six, will require three times as many terminals as there are speeds.

That is, a multi-speed motor with a single winding

on each member may be built for any number of speeds up to six, requiring no more terminals than if each speed were produced by a different winding. This does not mean that any arbitrary selection of numbers of poles can be built with no more terminals than abnormal combinations which fall outside the rule. Further research is rapidly lessening the number of these combinations.

A series of combinations adjusted with great care so as, on the one hand, to lend themselves to simple control,

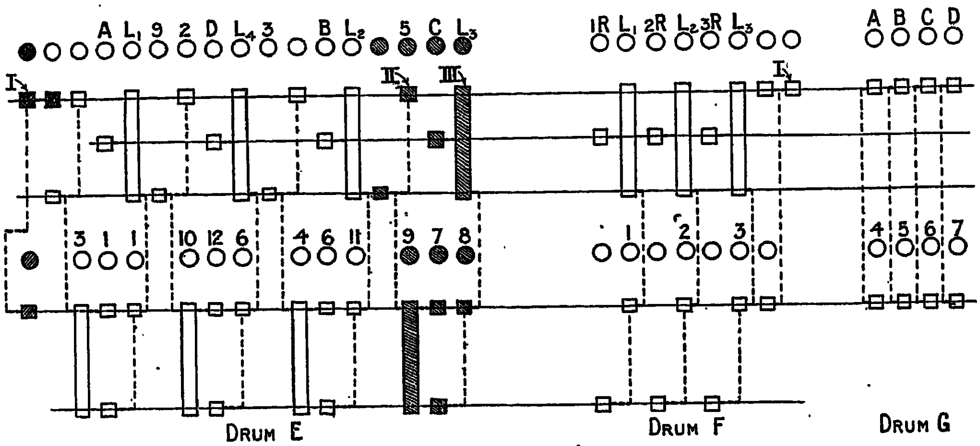

FIG. 12.

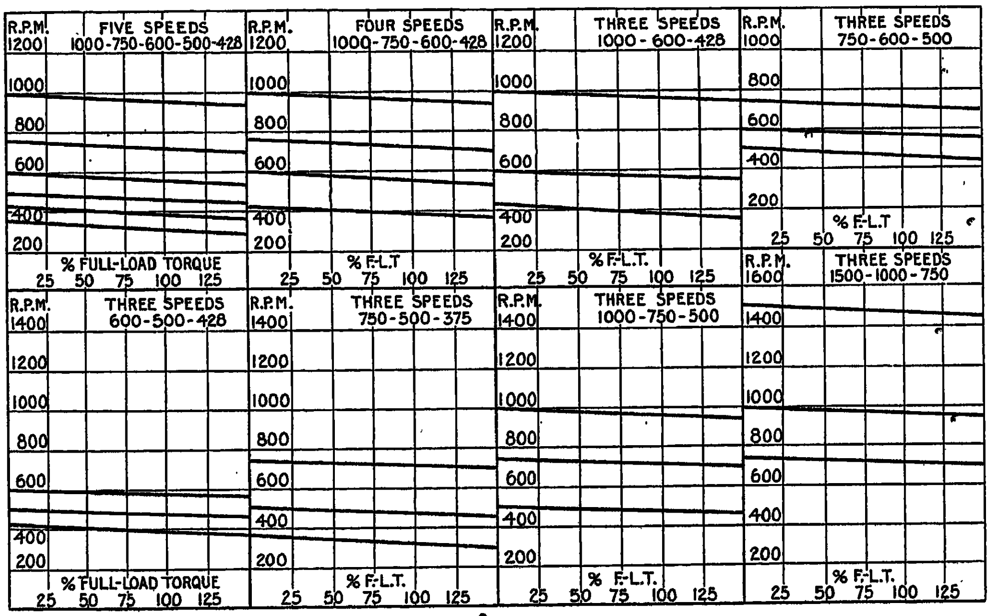

FIG. 13.

these, but that by suitably choosing the numbers of poles within the range of 3—1, these results may be obtained.

For instance, the winding described above (see Fig. 7) is usually arranged for 6, 10 and 14 poles, and requires 9 terminals, thereby obeying the rule, but a winding arranged for, say, 8, 10 and 14 poles, would not obey the rule, although windings for 6, 8 and 12, or 6, 10 and 12, could be designed to obey it.

Three is thus an amply sufficient selection of combinations for practical purposes, although there are a few and on the other to cover most industrial requirements, is shown in Fig. 11, covering speed-ranges on 50 periods as follows :—

1 500/1 000/750 : Drum F
1 000/750/500 : Drum F
750/500/375 : Drum F
750/600/500 : Drums F + G
1 000/600/428 : Drum A
1 000/750/600/428 : Drums A + C
1 000/750/600/500/428 : Drums A + B + C

It will no doubt be agreed that these combinations cover practically everything that is needed for industrial purposes, and the control of all of them is sufficiently simple to be dealt with by a drum controller. Figs. 11 and 12, in fact, show diagrams of the drum controllers which are used to give these combinations and it will be seen that all, except that for the five-speed machine, are simple pieces of apparatus requiring only a single drum. The five-speed machine is usually built with two drums geared together, and forms the only case in which this is necessary, while in Fig. 13 has been assembled a series of speed/torque curves giving one example of each speed combination.

An important point in connection with these machines is, of course, the cost as compared with other means of producing the same results. In Fig. 14 is given a curve, for different horse-powers, for machines of this type as compared with a slip-ring induction motor with its control gear. This curve ignores entirely the enormous economy of current secured by

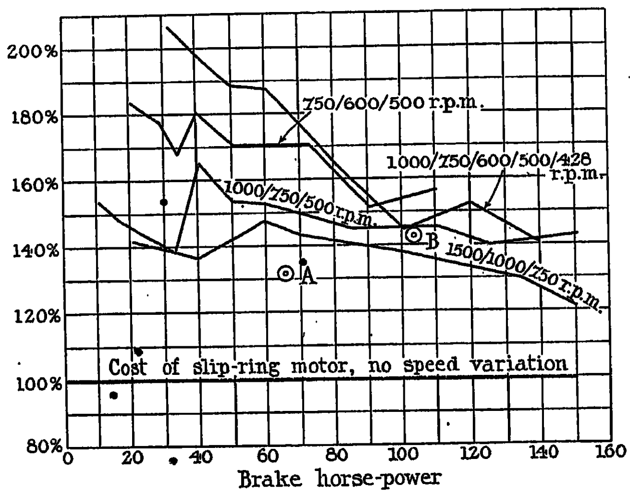

FIG. 14.—Percentage cost of multi-speed motors.

an apparatus of approximately constant efficiency on all speeds.

These controllers are suitable for small to medium sized motors, up to 200 h.p. The larger sizes, say from 200 h.p. to 800 h.p., are rather beyond the scope of a drum controller, and consequently an apparatus of a different type is employed. In Fig. 15 is shown such a large controller built by the Electric Construction Co., Ltd., the makers of these equipments, from which it will be seen that the controller consists of a slate panel bearing what are essentially four, nine-bladed two-way switches with vertical axes. The switches are of the finger type as in drum controllers and bear on studs mounted in the panel. They can be clearly seen in the lower half of the figure, while on the right and left of these switches are the terminals for the phase transformer and motor, respectively. The switches are opened and closed in the proper sequence by means of cams which appear immediately above the switches. For each speed, two of the switches make contact, thereby connecting the 18 terminals of the motor to the line or the phase transformer, in the different ways appropriate to different speeds.

It is found, by taking advantage of the following fact, that the switching may be simplified. One half of the connections for one number of poles, say 8, with the machine running clockwise, are identical with half the connections for another number of poles, say 10, with the motor running counter-clockwise. It conduces to simplicity of switching, therefore, if we make no change in these connections in changing from 8 poles to 10 poles, but merely interchange two of the three-phase lines, by means of the two contactors shown in the upper half of the panel which perform a quadruple function, as detailed below.

(1) They serve to reverse the three-phase connections when this is required, in order to economize switching.

(2) They are fitted with overload relays (shown immediately below them) so that they perform the function of a circuit breaker.

(3) In changing from one speed to the next in any multi-speed motor, it is necessary to open the circuit which in most forms of switchgear gives rise to a certain amount of arcing.

(I have for many years made it my practice in all such cases to open the circuit first, by a special switch designed with adequate blow-out apparatus, etc., to avoid arcing; then, while the motor circuits are completely dead, to change the connections, which may, of course, be done without any arcing, because they are not carrying any current; and, lastly, to close the main circuit again through the switch specially provided for that purpose. The contactors shown in the figure perform this function also.)

(4) The small switch on the right serves to open the contactor magnets, and causes them to act as a line switch, isolating the whole of the apparatus from the line as soon as it is opened.

The connections on the back of the board are not unduly complicated and are carried out by means of bare copper rods about $\frac{5}{16}$ in. diameter, in the standard manner. A mechanical interlock formed by the vertical rods below the contactors is fitted between the contactors and the cam shaft by means of an auxiliary shaft geared to the cam shaft, in the ratio of 1 to 4.

The operation of this interlock is as follows:—On making a slight movement of the controller handle, the contactor magnets are opened. No further movement is possible until both the contactors are fully opened. When this has taken place the shaft is freed, and on moving it further the cams begin to move and alter the adjustment of the main switches. When the handle of the controller has moved, say, 180°, then the adjustment has been completed and the magnet circuit of the contactors is re-energized, closing them when the machine continues to operate on the new number of poles. Although these operations take rather a long time to describe, they do not, in practice, take more than two seconds.

CHARACTERISTICS OF THE EQUIPMENT.

We now come to the description of the characteristics of machines of this type which are rendered available by the system of control just described. As has already

been pointed out, squirrel-cage motors of the multi-speed type can find a very much greater field of utility than when used on a single speed only, since the chief drawback is almost completely overcome in the multi-speed form. This advantage, of course, relates to the starting.

Consider, for instance, a 2-pole and a 4-pole motor, alternatively, for the same torque the 4-pole motor will require only half as much current; hence, if we can arrange a motor so that it starts on four poles and runs on two poles, to obtain a given starting torque it will take only half the starting current that it would require if it started on two poles. This is the origin of the very

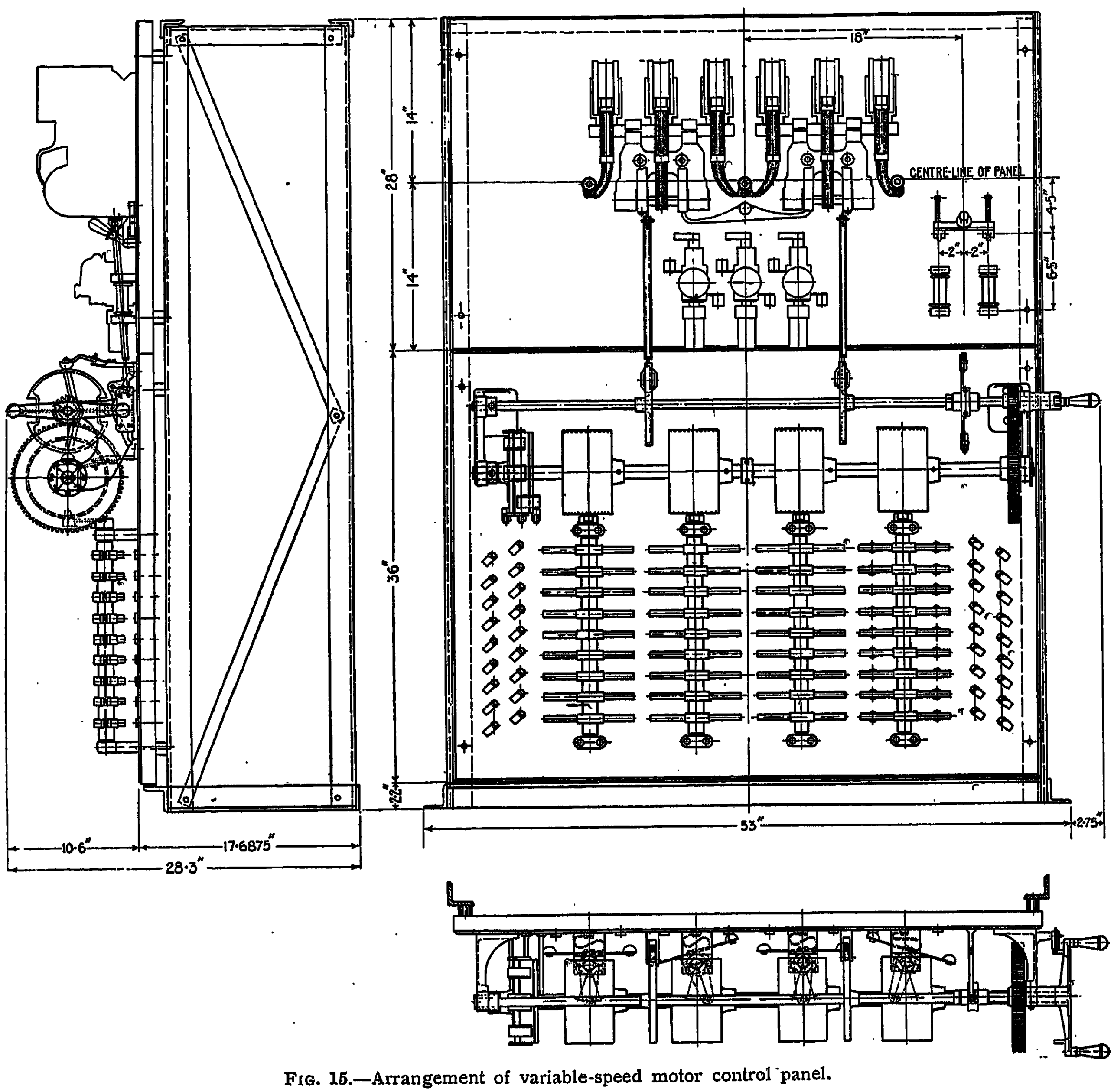

FIG. 15.—Arrangement of variable-speed motor control panel.

both having the same air-gap density. In the former there will be only two conductors in series, each lying in the middle of the pole-face, and the 4-pole motor will have four such conductors. If, therefore, we send the same current through the four conductors as through the two conductors, we shall obtain twice as much torque in the 4-pole machine as in the 2-pole machine, or, greatly improved performance of the squirrel-cage motor when used as a multi-speed machine. In squirrel-cage motors having a speed-range of two to one, or more, it is always possible to obtain full-load starting torque with not more than twice full-load current. All machines, of whatever size, having the same speed-range are capable of this ratio of starting torque to starting current, but

if switched straight on to the line larger machines frequently take much greater current and give correspondingly greater torques. In most cases, therefore, the use of an auto-transformer is necessary with large machines. This may be seen from Fig. 16, in which is shown starting torque plotted against starting current for a 4-, 6- and 8-pole motor built by Messrs. F. & A. Parkinson, Ltd. It will be seen that with the 8-pole connection the machine gives 1·7 times full-load torque with twice

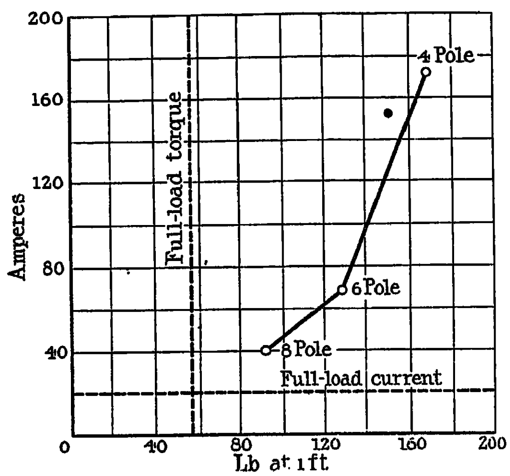

FIG. 16.

full-load current. With a 6-pole connection it gives 2·4 times full-load torque with 3·6 times full-load current. With a 4-pole connection it gives 3 times full-load torque with 8·6 times full-load current.

Another point frequently arising with multi-speed squirrel-cage motors relates to the current-rush on changing speed and the rate of acceleration from one speed to the next. Both these factors are under exact

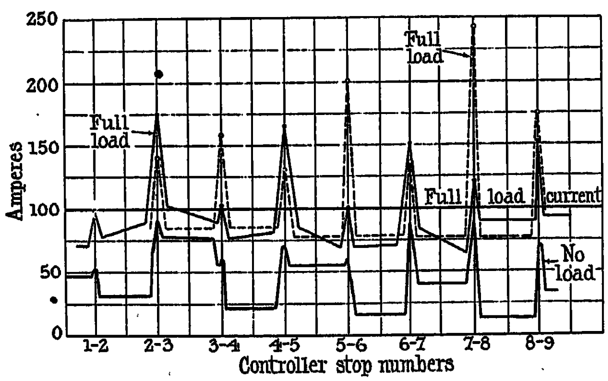

FIG. 17.

control by the use, in series with the motor, of primary resistance, which, of course, has the effect of reducing the voltage during the change of speed.

Returning to Fig. 15, in order to make use of this method of regulating the rate of acceleration between speeds, there is fitted on the panel by the side of those shown a third contactor which opens when they open, and which closes, due to the action of a dashpot, a few seconds after they close. This third contactor, when closed, bridges three resistances each placed in series with one of the lines; hence, directly the contactor opens, these resistances are placed in circuit, being adjusted to produce any desired rate of acceleration. They remain in series with the line during the operation of changing speeds, and are cut out when this operation has been completed.

In Fig. 17 are shown the current-surges produced in changing speed in a squirrel-cage motor arranged for all numbers of poles between 8 and 16, both with and without (dotted curves) a similar device, substituting an auto-transformer for the resistance. It will be seen that by its use the maximum current-surge is reduced to about one-half.

In a motor having a wide speed-range, the lowest

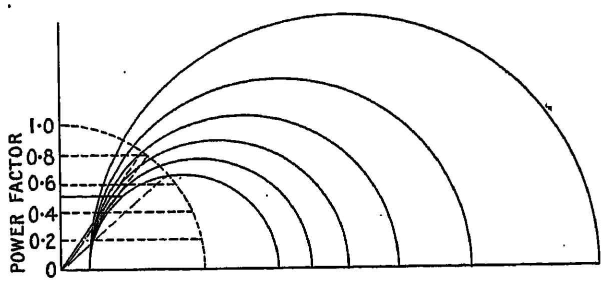

FIG. 18.

speed-steps are very small and there is seldom any need for such a device. It is on high speeds, however, that it is needed. The figure illustrates the marked reduction in the current-surge on these higher speeds (shown towards the right of the figure), the device of course being adjusted to suit this case.

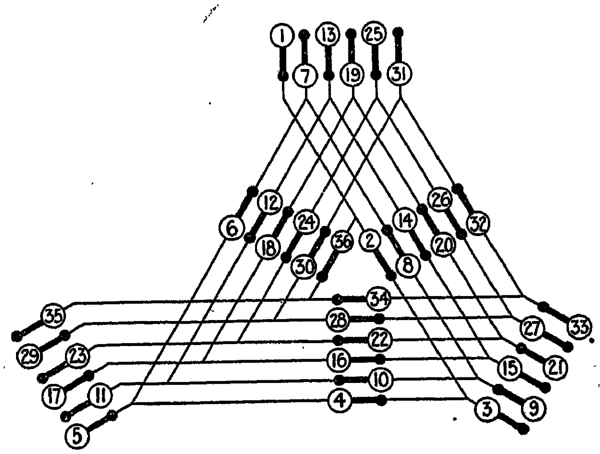

FIG. 19.

This method of starting and changing speed can be employed in motors up to several hundred horse-power, and renders the squirrel-cage motor adaptable to a vast variety of purposes for which it has never been found possible to use it before. A further extension of its field may be obtained by the use of centrifugal clutches, now coming into such general use, which may be arranged to operate at the lowest speed of the motor, the speed-

change from this point being arranged in the manner just described.

To sum up, the sequence of operations to change speed in the case of a squirrel-cage motor, for instance, would be as follows:—

(1) The first movement of the controller handle causes the contactor to open, thereby cutting off the supply from the installation and rendering it "dead."

(2) A further movement of the controller handle opens the "switch-units" and recloses them in the correct combination to suit the next speed and, as the supply is cut off meanwhile, the change takes place without any sparking.

(3) When the controller handle has been moved to the notch corresponding to the speed desired, the contactor closes again and the circuit is re-established, the whole operation of changing speed taking approximately two or three seconds and being accomplished by one movement of the controller handle. In Fig. 18 is shown a series of circle diagrams for such a multi-speed motor operating on all numbers of poles from 6 to 16 and absorbing the same magnetizing current in all cases. These diagrams assume that the leakage coefficient is proportional to the number of poles, thus being twice as great in a 12-pole machine as in a 6-pole one. It will be shown below that this assumption is very nearly fulfilled in this type of machine.

This figure shows clearly the cause of the very great economy in starting current which is found in practice and was illustrated in Fig. 16. It will be seen that with 16 poles the motor takes about one-third of the starting current required with a 6-pole connection. Since the motor gives the same torque at all speeds, the ordinates to each circle represent the torque to a scale such that the torque represented by 1 mm on the diagram is proportional to the number of poles. Hence, in spite of the small current consumption, the motor can yield a powerful starting torque at the lowest speed.

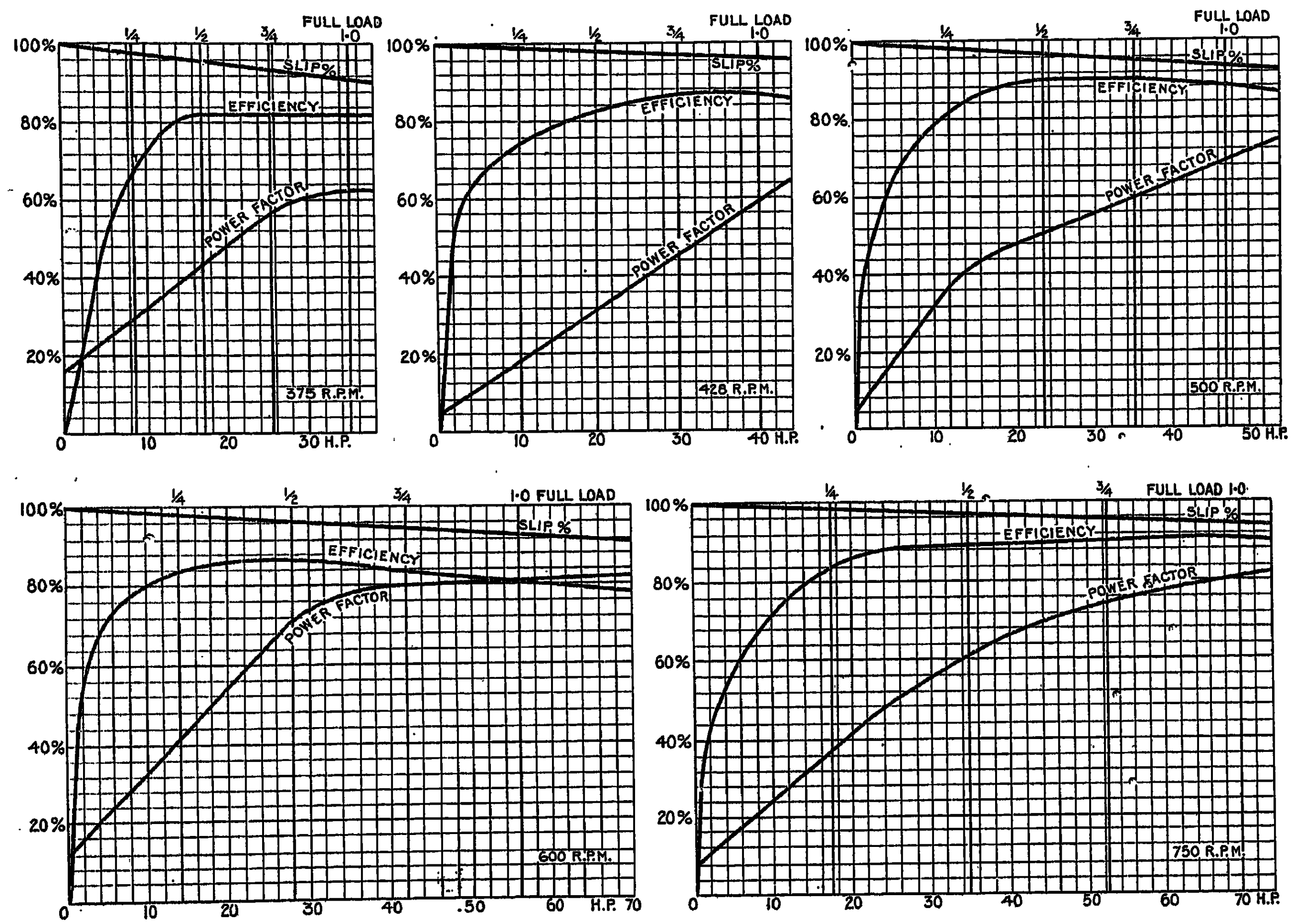

Fig. 20.—Performance curves with high-resistance rotor.

Slip-ring motors.—It is possible to design a rotor winding for a machine having any number of speeds which shall give genuine slip-ring control up to one of these speeds, for instance, the top speed, and operate as a short-circuited secondary winding on all other speeds. One convenient way of effecting this result is by using such a winding as is shown in Fig. 6 but permanently connected so as to be capable of direct connection to the line. This connection is shown in

Fig. 19 and it will be seen that, as so connected, the winding requires no more than three terminals and can therefore be connected to the usual number of slip-rings.

On all other numbers of poles than six, however, the winding would require more than three terminals to enable it to be connected to any outside circuit, and if these terminals are short-circuited the winding is also internally short-circuited. Hence, the secondary currents which on 6-pole operation flow through the slip-rings, on any other number of poles flow through the internal circuits of the winding and do not pass through the slip-rings at all.

By means of this construction a motor is produced which can be arranged to be accelerated, by means of an ordinary resistance connected across its three slip-rings, from standstill to any one of its six speeds, starting, if desired, with from 2 to $2\frac{1}{2}$ times full-load torque. On reaching the speed at which it is desired to run, a movement of the controller handle changes the number of poles of the motor to the desired value, when the currents in the rotor winding are automatically diverted from the slip-rings and continue to flow in closed circuits in the winding.

The operation of starting the slip-ring motor on any other than the top speed is therefore as follows:—

(1) Set the controller to the starting position which will produce in the motor a number of poles corresponding to the top speed.

(2) Gradually close the starting rheostat, when the motor will speed up.

(3) When the motor has reached the speed desired, which will of course be less than top speed, move the controller from the starting position to the running position corresponding to the speed at which it is running. This will have the effect of changing the number of poles to that corresponding to the controller notch employed, when the starter is automatically cut out as already described and the motor continues to run with its rotor short-circuited.

(4) The starter may now be open-circuited at leisure.

A tachometer may be provided in order to enable the operator to know the proper moment to change from starting to running position.

In Figs. 20 and 21 are shown some curves of efficiency and power factor of a 70 h.p. motor arranged to give all numbers of poles from 8 to 16.

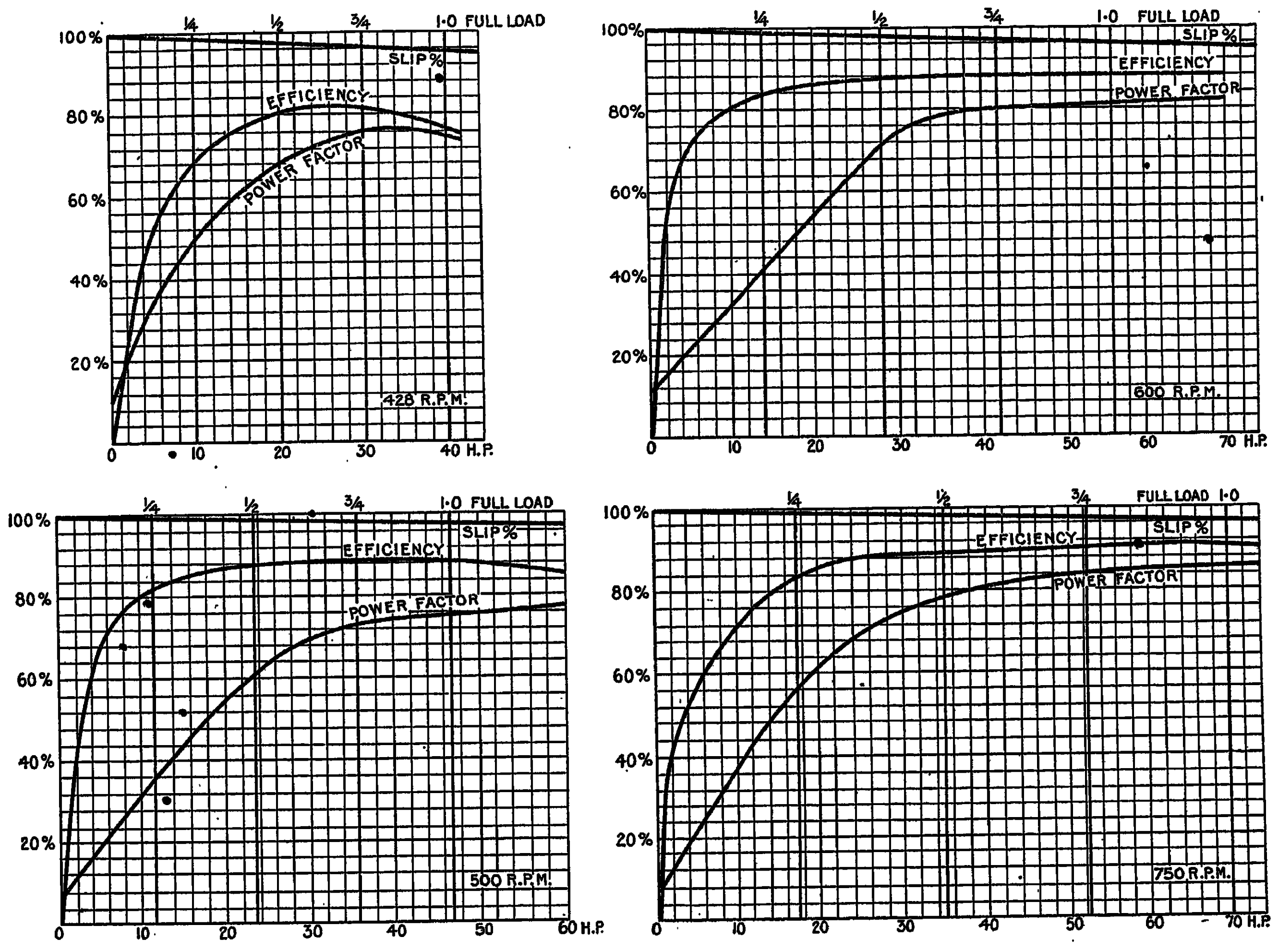

FIG. 21.—Performance curves with normal low-resistance rotor.

Fig. 20 shows efficiency, power factor and slip curves for the 70 h.p. motor referred to above, arranged to give all numbers of poles from 8 to 16. These curves correspond to the results obtained when fitted with a high-resistance rotor adapted to give the powerful torque required in connection with this motor.

Fig. 21 shows corresponding curves for the same machine when fitted with a normal low-resistance rotor commonly used with squirrel-cage machines. Comparing these two sets of curves, a result will be noticed which at first appears rather strange, namely, that the efficiencies of the machine with a high-resistance rotor and with a low-resistance rotor are not very different for the same speed, while the power factor of the machine with high-resistance rotor is a good deal less than that of the machine when fitted with low-resistance rotor.

This is due to a method which can be employed in the induction motor to enable a high-resistance rotor to be employed without loss of overall efficiency. The torque of the motor is, of course, proportional to the product of ampere-conductors by flux density. If, therefore, we compare two motors having, say, flux densities in the ratio of 1·5 to 1, then in order to give the same torque they will require a number of rotor ampere-conductors in the ratio of 1 to 1·5, the machine having the stronger flux density requiring only two-thirds of the current in the rotor bars required by that having the smaller flux density. Two-thirds of the rotor current means of course four-ninths, or less than half, of the rotor I^2R loss and, consequently, if we desire the resistance loss to be the same in both cases, the machine with the stronger flux density may have $2\frac{1}{4}$ times the rotor resistance of that with the weaker flux density.

This method was adopted in the motor illustrated in the above figures, which by means of tappings on the transformer was adapted to operate with either a strong or a weak flux. The strong flux used with the high-resistance rotor involves, of course, low power factor, and this is the explanation of the nature of the curves shown. By using stalloy steel punchings the iron loss was reduced to such a small proportion of the whole that the increased iron loss due to the stronger flux produced only a negligible effect on the efficiency.

Thus, by this process the squirrel-cage motor can be adapted to give any desired starting torque, without loss of efficiency, wherever we are prepared to sacrifice power factor to obtain this result, or to use additional power-factor-compensation devices such as condensers.

Power factor and efficiency.—Referring to the curves given above, it may be seen that the characteristics of the machine as regards power factor and efficiency are, broadly speaking, as follows :—

The efficiency remains very nearly the same at all speeds, though there is a slight reduction at reduced speeds, due, broadly, to the fact that the losses remain approximately constant at all speeds, while the output, of course, falls off in proportion to the speed. In the larger sizes, this reduction in efficiency will seldom exceed 5 per cent. The efficiency at top speed is, of course, practically the same as in a standard motor. The power factor also varies, as we change speed, to a somewhat greater degree than the efficiency, this variation being due, broadly speaking again, to the fact that the magnetizing current remains the same at all speeds, while the true power input falls off proportionately to the reduction of speed. Again, in the larger sizes this variation will seldom exceed 10 per cent.

The only thing which needs to be borne in mind from the power supply point of view is that these machines absorb a constant amount of wattless current at all speeds, and that this amount is not greater than that absorbed by a standard machine having the same

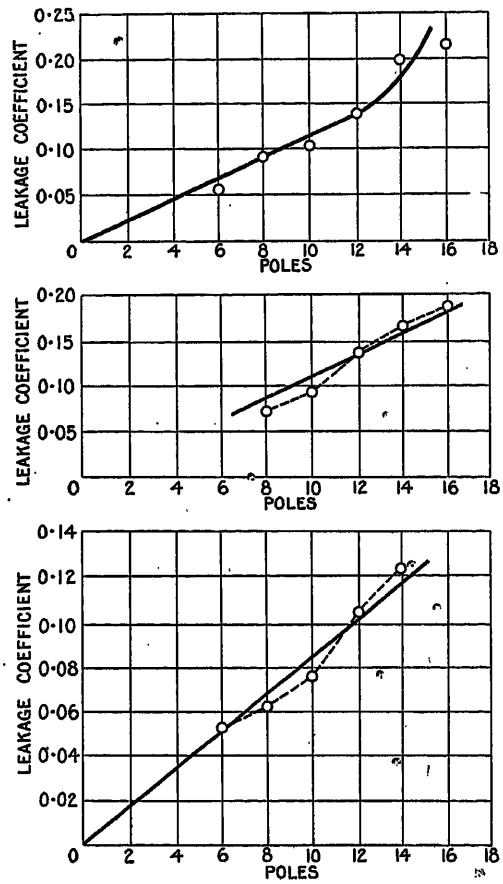

FIG. 22.

rating. Perhaps it may serve to make the matter clearer if we compare the equipment with a standard motor driving through a gear box, a load which requires constant torque at all speeds. At top speed the motor is fully loaded and operates with its best power factor and efficiency. As the speed and the load are reduced by changing gear, the output of the motor falls off and with it the power factor and efficiency to some extent. To almost exactly the same extent do the power factor and efficiency of the equipment described fall off when the load is reduced; in fact, the controller described above may be regarded as an electrical method of changing gear.

Reference has been made above to the fact that the

leakage coefficient of these machines is practically proportional to the number of poles, and in Fig. 22 are shown some curves of leakage coefficients plotted against the number of poles. These curves illustrate this feature. Such curves, it is believed, will be of considerable interest to designers, and clearly could not be obtained from any other type of motor except one retaining an absolutely identical winding on all numbers of poles. Comparisons have frequently been made between motors having different numbers of poles, but this, of course, is not at all the same thing as in the case of a single multi-speed motor.

One of the marked advantages of a cascade set is that it is possible to obtain not only two efficient speeds but also resistance control from standstill to the lower speed and, in addition, resistance control from the lower speed to the top speed. If the rotor of the second machine is fitted with slip-rings, then, if the first machine is connected to the line and the slip-rings of the second machine are gradually short-circuited through a resistance, the machine will start and rise gradually in speed, being under complete control by means of the rheostat, to the lower of its two efficient speeds, which it reaches when the slip-rings are completely short-circuited. If

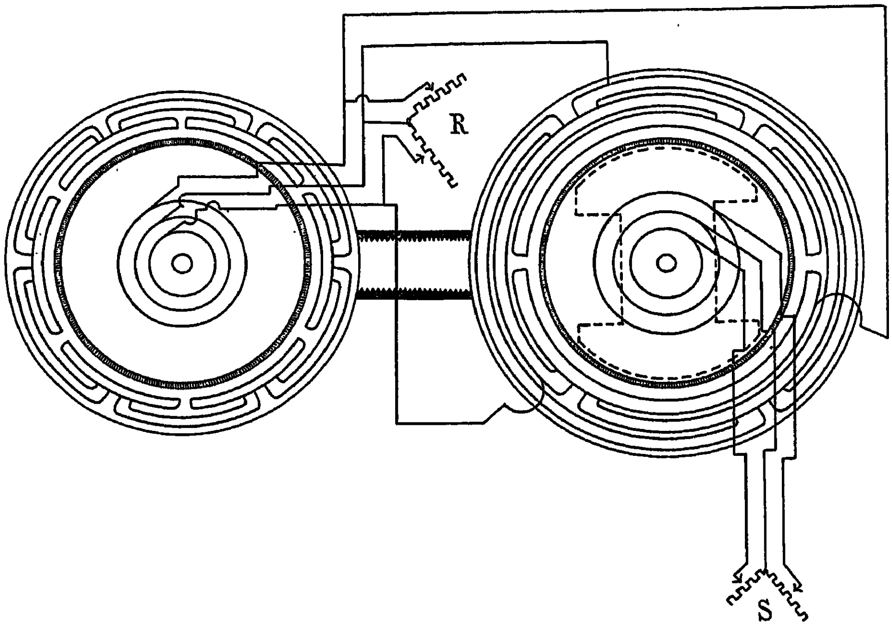

FIG. 23.

we now connect a similar resistance across the slip-rings of the first machine, then, on gradually short-circuiting them, the machine will rise from its lower efficient speed, say 750 r.p.m., to the higher, 1000 r.p.m.,

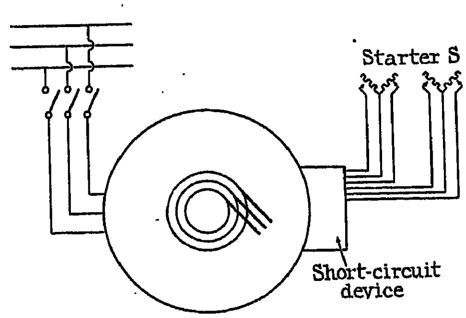

FIG. 24.

which it reaches when the slip-rings of the first machine are short-circuited, and the second machine is thereby entirely cut out of action.

The advantages of these characteristics are, of course, very great, and the peculiar merit of Mr. Hunt's invention consists in having enabled us to realize them

Part 2.

THE CASCADE MOTOR.

As previously pointed out, a second line of progress in the development of the induction motor leads in the direction of the internal cascade machine, as originally invented and developed by Mr. L. J. Hunt, but which has recently undergone very great further developments which have adapted it to a very much larger field.* The cascade machine has been described before the Institution several times in recent years and therefore I need only describe its principles very briefly, laying more stress on the different practical forms which it assumes and on the functions which it is capable of performing in the general system of electric power supply.

We may first of all briefly recall the general principles of a cascade operation. In Fig. 23 are shown two machines mechanically coupled together, in which the slip-rings of the first are connected to the stator winding of the second. The second machine is assumed to be wound for two poles and the first for six, and the combination will run at 750 r.p.m. on a 50-period circuit, viz. at a speed corresponding to (6 + 2) poles.

* F. CREEDY: "Some Developments in Multi-speed Cascade Induction Motors," *Journal I.E.E.*, 1921, vol. 59, p. 511.

practically in one machine instead of two, whereby all the disadvantages of poor power factor and efficiency and higher first cost, which are inherent in the use of two distinct machines, are avoided.

How this has been accomplished has very recently been described before the Institution,* so I will not discuss it again. It will be sufficient to say that the final result is a motor as shown in Fig. 24 having only

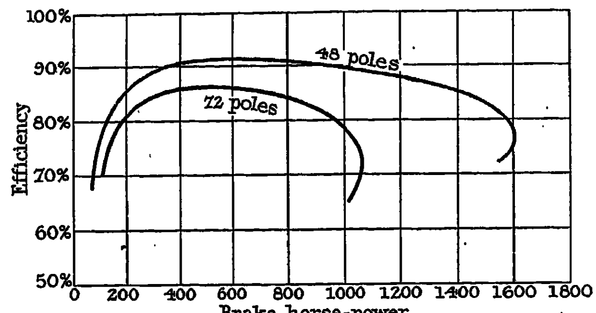

FIG. 25.—Efficiency curves of a Sandycroft two-speed cascade 3 000 volt, 50 period rolling-mill motor; 860 b.h.p. at 120·5 r.p.m., and 576 b.h.p. at 81·6 r.p.m.

a single winding on each member, the stator being connected, on the one hand, to the line as a primary winding, and on the other to a starter as shown, the resistance of which is gradually cut out in order to bring the machine from standstill up to its cascade speed. This having been done, on further short-circuiting the resistances R placed across the slip-rings the motor will rise from its cascade speed to its maximum speed.

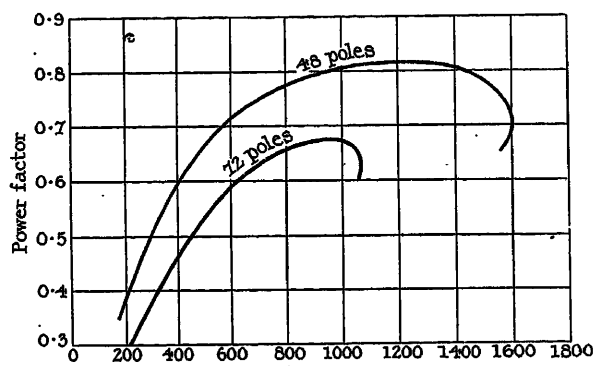

FIG. 26.—Power factor curves for the motor referred to in Fig. 25.

An alternative method of operation consists in having both sets of slip-rings on the one rotor and thus obtaining for a particular combination of numbers of poles a machine with six slip-rings, the same number as are required in the cascade set. By short-circuiting three of these through a resistance, the machine is brought up to its lower speed, while by short-circuiting the remaining three it is brought up to its top speed. This method of starting is particularly advantageous for high-tension machines, since it avoids all high-tension switchgear and forms the only multi-speed induction motor in which it is possible to change speed without opening the circuit.

Internal cascade machines of this type, however, as built up to recent years were restricted to machines having their lowest efficient speeds corresponding to numbers of poles of 12, 18 and 24, etc., and to two definite ratios of speeds, namely, 3—2 and 3—1. While much work has been accomplished by this means, and great credit is due to Messrs. Sandycroft for the results obtained, it is believed that now that these limitations have been removed they will be able to cover a much wider field. Machines can now be built the lowest speeds of which correspond to any number of poles exceeding six and having, in theory, any desired ratio of speeds. Certain practical limitations to the speed ratios of two-speed motors are introduced by the rule as regards the number of slip-rings required by such a machine. This rule is as follows:—

A motor to give a top speed corresponding to M *poles and a bottom speed corresponding to* (M + N) *poles, will have a number of slip-rings equal to* (M + N)/(G.C.M. of M and N).

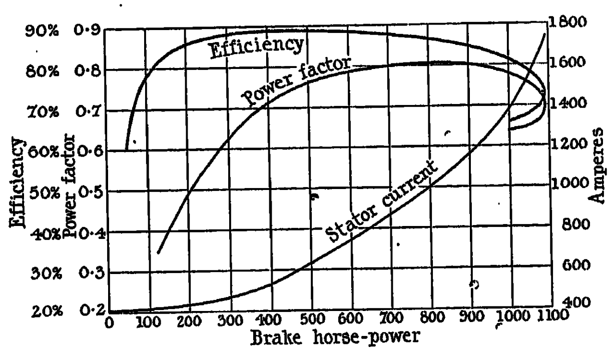

FIG. 27.—Performance curves of a single-speed, 450 b.h.p., 122 r.p.m., 500 volt, 50 period rolling-mill motor.

For cases where either M or N is large and where there is no common factor between them, clearly the number of slip-rings may be higher than is desirable, but setting aside these cases a very large number of new ratios become available. For instance, confining ourselves to apparatus requiring less than six slip-rings the following combinations, among others, can be built:

Ratio	Speeds offered on 50 periods
4—3	1 000/750 or 500/375, etc.
5—4	750/600 or 375/300, etc.
5—3	500/300 or 250/150, etc.
5—6	600/500 or 300/250, etc.

Some of these ratios are particularly important in certain classes of application, e.g. in mine fan motors where the power developed decreases as the cube of the speed. In these cases the reduction from full speed to two-thirds is sometimes found to be too great and a smaller reduction, say from full speed to 5/6 or 4/5 full speed, may meet the conditions more fully.

Besides this, only a very small reduction is necessary for flywheel sets and in this case the new ratios prove also of very great advantage.

* F. CREEDY: "Some Developments in Multi-speed Cascade Induction Motors," *Journal I.E.E.*, 1921, vol. 59, p. 511.

The slip-regulator operating the rotor circuit of a two-speed cascade motor wastes very much less power, and consequently may be of very much smaller and lighter construction than when used with an ordinary single-speed induction motor.

Curves relating to a two-speed rolling-mill motor of considerable size in which these properties of the cascade motor are made advantageous use of are shown in Figs. 25 and 26, which, I think, will be found to be self-explanatory. In Fig. 27 are shown performance curves of a single-speed cascade rolling-mill motor which was adopted on account of the absence of slip-rings, and the singularly substantial construction of the rotor winding, both of which are of great importance in steel-mill work.

So far we have dealt with the cascade set pure and simple, in which the speed-change can be effected without opening the stator circuit. By combining the cascade method with the pole-changing method previously described, machines may be built for three or more speeds. To do this the primary winding is adapted for several numbers of poles, which may be done in a variety of ways, although, due to its double function as primary of the first machine and secondary of the second machine, this is more difficult than where the winding only has to serve a single function as described in Part 1. The same cascade speed may be obtained by means of several different combinations of numbers of poles; for instance, a cascade speed of (8 + 4) = 12 poles, may also be obtained from (10 + 2) = 12 poles, and it has been proved that a secondary winding which is adapted to work with (8 + 4) poles will work equally well with (10 + 2). Hence, if we have the primary winding of the machine arranged for 8 poles, and the secondary winding adapted to (8 + 4), the machine, if running on its cascade speed, will go at the speed corresponding to 12 poles and, if we short-circuit the slip-rings, will rise from the 12-pole speed (500 r.p.m.) to the 8-pole speed (750 r.p.m.).

If, while the machine is running at its cascade speed (500 r.p.m.), we change the number of poles in the stator winding from 8 to 10 which, of course, involves a switching operation, there will be no change in the speed of the motor. If, however, we now short-circuit the slip-rings, the machine will gradually rise from the 12-pole speed (500 r.p.m.) to the 10-pole speed (600 r.p.m.). Thus we have an apparatus preserving the unique characteristic of the cascade machine, viz. that of permitting a gradual regulation between speeds and yet having more than two speeds.

Large, low-speed motors having speeds in the ratios just mentioned, e.g. motors running at 187/150/125 r.p.m., prove very advantageous in certain cases, for instance in rolling mills. The principle just described may be extended to machines having four or more speeds, in all of which cases the cascade machine will rise from its cascade speed to any of the speeds for which the stator winding is adapted.

For instance, a four-speed machine adapted to speeds of 750/500/375/300 r.p.m. may be built. The limitations to the number of speeds which can be obtained by this process are due to the difficulty of designing the stator winding for a large number of different numbers of poles, and at the same time adapting it to act as a secondary.

Other applications of the cascade machine.—In addition to its usefulness as a multi-speed machine, the cascade induction motor has a wide field of utility in other directions to which we may briefly refer. It has been pointed out that it may be started with a powerful torque and brought up to its cascade speed by merely cutting out a resistance connected across the tappings on the stator winding. Such a machine will have a completely short-circuited rotor without external connections, and it realizes the old desideratum of a squirrel-cage motor with slip-ring characteristics.

I need not do more than very briefly point out the great advantages of such a construction in dusty or inflammable atmospheres, and its much greater reliability.

It has often been pointed out that the power factor of the cascade motor is materially higher than that of the standard type of slip-ring induction motor running at the same speed. This is due to the following two causes :—

(1) A cascade motor running at 500 r.p.m. is wound for 8 poles, and therefore the pole-pitch is 50 per cent greater than in a standard 12-pole motor. The difference in leakage between an 8-pole and a 12-pole motor is very considerable, as may be seen in Fig. 22.

(2) The simple cascade rotor winding, approximating as it does more nearly to a squirrel-cage winding than to an ordinary slip-ring winding, gives rise to a much lower leakage, and these two causes, acting in conjunction, account for the higher power factor of the cascade machine.

Another application, which may possibly prove to be the most important of all, is as a synchronous machine for the purpose of improving the power factor. Such a machine has marked advantages over any other form of synchronous apparatus.

The chief drawback to synchronous sets for improved power factor has up to now been their high cost, which is largely due to the amount of auxiliary apparatus they require, in addition to the large number of exciting ampere-turns necessary to give an adequate overload capacity. Both these features are very much reduced in the synchronous cascade set.

In order to understand this, consider a cascade set, consisting of two machines, the stator of the second of which is electrically coupled to the slip-rings of the first, while they are mounted on a common shaft. Let the second machine be arranged for two poles and the first machine for six poles, then, as is well known, the combination will run at 750 r.p.m. on a 50-period circuit, viz. at a speed corresponding to (6 + 2) poles.

The second machine will receive from the slip-rings a frequency one-quarter the line frequency, viz. 12·5 periods per second. As is well known, the rotor of the second machine of the cascade set may be of any desired type, e.g. either of the squirrel-cage type, the slip-ring type, or even the revolving field of a synchronous motor.

On the rotor of such a secondary synchronous motor a number of ampere-turns must be provided, equal to that on the stator, plus the amount necessary to produce the magnetic flux in this secondary machine.

Now, in the internal cascade motor, the ratio of the total flux (flux per pole × number of poles) in the

parts corresponding to the primary and secondary motors in the cascade set which we are now discussing, is fixed by the construction of the rotor winding and is nearly equal in both cases. Consequently, a cascade set corresponding to the internal cascade machine would have the same total flux in both its constituent machines. If the magnetic densities are the same, as they must

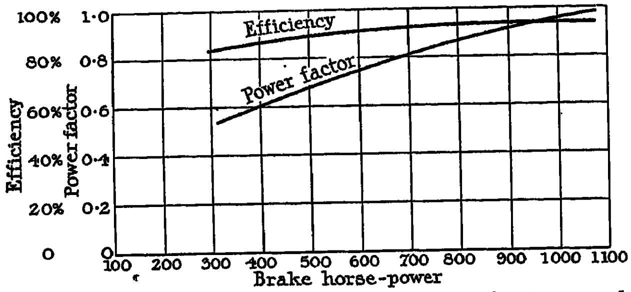

FIG. 28.—Efficiency and power-factor curves of a two-speed, 3 300 volt, 50 period, three-phase synchronous fan motor; 850 b.h.p. at 187·5 r.p.m., and 260 b.h.p. at 125 r.p.m. Curves for 187·5 r.p.m.

be, since both fluxes are carried by the same iron, it follows from fundamental electromagnetic laws that the turns per pole necessary to produce these fluxes in the primary and secondary machines are also nearly equal, and, since there are only two poles in the secondary motor to be excited instead of eight poles in a synchronous motor of normal construction running at the

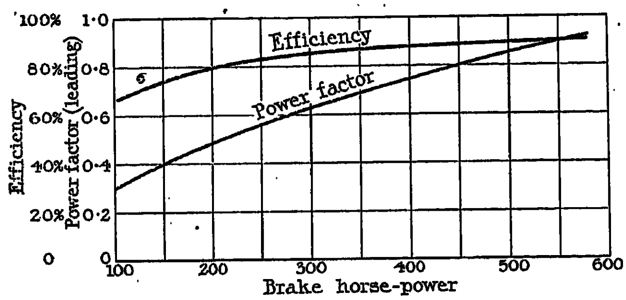

FIG. 29.—Efficiency and power factor curves of the motor referred to in Fig. 28, at 125 r.p.m.

same speed (750 r.p.m.), only one-quarter of the exciting watts are needed.

This shows itself in practice in the very much reduced size of exciter required by a cascade synchronous motor as compared with the older type. This characteristic renders the synchronous cascade motor feasible from the point of view of cost in much smaller sizes than any other type of synchronous machine. Figs. 28 and 29 show characteristics of a two-speed cascade synchronous machine of this type.

SUMMARY OF CHARACTERISTICS OF VARIABLE-SPEED, ALTERNATING-CURRENT MOTORS WITHOUT COMMUTATORS.

(1) A large variety of speed combinations is available, giving any number of speeds up to five (or six with a panel-type controller), e.g. those shown in Fig. 13, all of which are capable of control by simple types of drum controller and some are capable of being built economically down to 2 or 3 h.p.

These have, for the most part, the characteristics of machines with short-circuited secondaries, but are capable of starting at full-load torque with not more than twice full-load current, and the rate of acceleration in changing speed under full load is under exact control by simple means.

(2) A slip-ring type of motor capable of any number of speeds up to six and capable of accelerating under, say, 2–2½ times full-load torque from standstill to any of such speeds.

(3) The two-speed cascade motor capable of accelerating from standstill to its lowest speed under 2–2½ times full-load torque by resistance control, and then rising from its lower to its higher speed by short-circuiting a resistance connected across the slip-rings. These two speeds may have practically any desired ratio. Speed-change is here effected without opening the stator circuit.

(4) A multi-speed cascade machine capable of starting and accelerating to its lowest speed in the manner just described and then of rising from that speed to any one of its other speeds on short-circuiting the slip-rings.

I believe it will be admitted, as a result of what has been said above, that it is possible to meet practically every condition of variable-speed working required in industrial practice by an appropriate method of control applied to the ordinary induction motor, this control involving no continuous waste of power or other undesirable features, and consisting merely of simple and well-known types of switchgear and, in some cases, small transformers.

For the few remaining cases in which an absolutely gradual speed-variation is required without loss of power, we have the polyphase commutator motor, with movable brushes as was described, for instance, in the paper by Mr. Teago.*

Hence I feel that I should have no difficulty whatever in recommending a suitable variable-speed alternating-current motor to meet the conditions of any industrial problem whatever, and that no cases remain in which it is either necessary or desirable to convert to direct current for the sake of obtaining variable-speed operation.

* *Journal I.E.E.*, 1922, vol. 60, p. 328.

DISCUSSION BEFORE THE INSTITUTION, 4 JANUARY, 1923.

Mr. L. J. Hunt: I propose to confine my remarks mainly to the windings. It is, I think, a remarkable fact, and one which will appeal to the manufacturer, that the winding which has made practicable the building of commercial cascade motors is apparently also the best winding for variable-pole motors. I refer to the old cascade rotor winding which, as the author has shown, gives quite remarkable results when used as a stator winding for change-pole motors. Before the author studied this winding it had been used only for three-phase and six-phase currents, and as a variable-pole winding produced either x or $2x$ poles.

The unit winding was a six-sided figure which served for a six-pole cascade motor. The other windings were built up as multiples of this unit and so we had a 12-sided figure for 12 poles, an 18-sided figure for 18 poles, and so on, the windings being parallel connected. The author's first discovery was that these windings would always give a cascade speed corresponding to a number of poles equal to the number of sides, irrespective of the number of poles for which the stator was wound; thus an 18-sided winding would give a cascade speed corresponding to 18 poles with a stator connected for either 16, 14, 12, 10, 8, 6, etc., poles, the number of auxiliary poles produced by the rotor being the difference between 18 poles and the number of poles for which the stator is connected. Further, he found that when the slip-rings were short-circuited the winding would serve as a satisfactory secondary winding for any of the basal numbers of poles; that is to say, if the stator were connected for six poles the winding would serve as a six-pole secondary winding or, equally well, as a secondary winding for the other numbers of poles. This discovery immediately pointed the way to the remarkable developments which the author has shown us. When used as a rotor winding the difference in phase between the several slip-rings varies with the number of poles provided by the stator. It follows therefore that if we use this winding as a primary and supply it with currents, the phase of which can be correspondingly changed, we shall produce the same variations in the number of poles, and this the author has done by means of the beautifully worked-out phase transformer which he has described. Fig. 6 is familiar as the 18-pole cascade rotor winding, which before the author's discovery had been used only for basal numbers of poles of 12 or 6, corresponding to three-phase or six-phase currents; that is to say, this winding prior to these new developments had been used for only 6 or 12 poles or, in cascade, for 18 poles. The author has shown how very efficient it is when used as a stator winding for producing a large number of speeds. He made a further discovery applicable to both change-pole and cascade motors. He found that in the past we had needlessly confined these windings to three-phase and six-phase types, and he showed that an 8-sided winding would operate as an 8-pole cascade rotor, a 20-sided winding as a 20-pole machine, and so on. In his recent paper * he defined these windings as suitable for use with two fields having numbers of pairs of poles prime to one another and both odd. These windings greatly increased the possible speeds for which cascade motors could be wound, as they gave us 8, 16, 20, etc., poles. This greatly increased the scope of the motor, but further discoveries were made. Dr. F. T. Chapman, in his recent paper on "The Production of Noise and Vibration in Certain Squirrel-cage Induction Motors," † has proved that no unbalanced magnetic pull exists when a motor is subjected to two magnetic fields if the difference between the numbers of poles is greater than two. This further increases the possible numbers of poles for which cascade machines can be wound, as it shows that all speeds can be obtained excepting those corresponding to 2, 4 or 6 poles, because a 10-pole motor can be obtained by taking basal numbers of poles of 8 and 2, thus giving a 10-sided winding, and with the stator wound for 8 poles the rotor would produce a second field corresponding to 2 poles. These discoveries enormously increase the field for these machines. The author has referred to the reduced excitation required by synchronous cascade machines, and I have some figures derived from tests which show that a machine of this type with sufficient ampere-turns to give a maximum torque equal to twice full-load torque requires a net number of field ampere-turns equal to only 61·4 per cent of the total stator ampere-turns. If allowance is made for the cancelled bars due to the shortened pole-pitch of the windings, the figure is 4 per cent greater than the alternating-current ampere-turns. The following figures relating to ship-propulsion motors may be of interest. They relate to a unit driving one propeller shaft. This is arranged for full speed, two-thirds and one-half speed, and develops 20 000 b.h.p., 5 000 b.h.p. and 2 600 b.h.p., respectively, at the three speeds. At full speed the set runs as an induction motor, and at the other speeds as a cascade synchronous combination. At full speed (24 poles) the power factor is 0·91 and the efficiency 96·5 per cent, while at second speed (36 poles) the efficiency is 94 per cent and the power factor unity. At half speed (48 poles) the efficiency is 93·2 per cent with unity power factor. There are many points to be considered in the design of multi-speed motors, and two slides which I propose to exhibit show the great improvement which can be effected in the performance of these machines by using three groups of coils per pole, instead of three groups per pole pair. These figures relate to a 400-b.h.p., three-speed motor which was built many years ago. In the first place the stator was wound with three groups of coils per pair of poles, and the efficiencies and power factors obtained can be seen on the slide. At a later date the motor was reconnected with the coils arranged in three groups per pole, and the vast improvement in both efficiency and power factor is shown. At 20-pole speed the efficiency improved from 87 to 90·5 per cent and the power factor from 0·795 to 0·9. At 30-pole speed (cascade) the efficiency was raised from 80 to 87 per cent and the power factor from 0·665 to 0·79. These figures are rather remarkable, as they indicate the harmful effects due to the presence of extraneous fields.

Dr. S. P. Smith: The author's achievement in the field of the variable-speed induction motor is no mean one, and he has given us what we very much needed. The fact that the induction motor could not be made to vary its speed economically by any simple means has been one of the greatest drawbacks in its development. We have long had various arrangements of two machines and also of two windings on a single machine, but the author now shows how to make the ordinary squirrel-cage induction motor run at 2, 3, 4, 5, or even 6 economical speeds. In that way he has rendered us a very great service and has made it possible to avoid, in many cases, converting alternating into direct current. The author's multi-speed motor has advantages in addition to its speed-changing properties. With an

* *Journal I.E.E.*, 1921, vol. 59, p. 511.
† *Ibid.*, 1923, vol. 61, p. 39.

ordinary squirrel-cage single-speed motor, if full-load torque is required at starting, something like 4 to 5 times full-load current is needed. Except in the case of small motors the supply undertaking would not allow this, and therefore a slip-ring motor must be used. The multi-speed motor, however, can give full-load torque with twice full-load current, which should not be objected to on large systems. Another advantage which should be emphasized is that the multi-speed motor will give constant torque at all speeds. The shunt motor has not this advantage. Assuming constant armature current in a shunt motor, the torque falls off as the speed rises, so that the horse-power remains constant. What the user generally wants for many classes of drives, however, is constant torque, or output proportional to speed. This property can be obtained with the a.c. motor with or without a commutator. The reason is simple. In order to make the horse-power increase as the speed rises, the voltage must be increased. It is complicated to do this with direct current, but with alternating current it is usually a simple matter to utilize the motor fully under all conditions. Fig. A will enable the interior of the author's multi-speed motor to be seen from a different point of view. The arrangement is shown for a thirteen-phase transformer or phase converter. With 13 phases on the transformer the angle between the phases is $2\pi/13$ radians. The numbers in the figures refer to the numbers of the transformer phases. The top left-hand figure shows that the motor tappings 1, 2, 3, 4, etc., are connected to phases 1, 2, 3, 4, etc., of the transformer. Thus for one pole-pair, or 2π radians, we must go round the whole periphery. In the middle diagram on the top line the author would connect phase 1 of his transformer to tapping 1 of his motor, but phase 3 of his transformer goes to tapping 2 of his motor, and so on, so that the phase angle would now be $4\pi/13$. One pole-pair (2π radians) is now accomplished with a half-tour of the stator winding, so that the motor has four poles ($p = 2$). Similarly the other possibilities give $p = 3$, 4, 5 and 6 pole-pairs. Thus the thirteen-phase transformer will give a six-speed motor. On the author's motor an 18-phase arrangement is used to simplify the connections, tappings, etc. By using the multi-speed or extended cascade motor, it may be possible to dispense with speed-regulating sets such as the Scherbius. It will be interesting to see whether these arrangements can be used for large, reversible sets such as rolling mills, winding engines, etc. There still remains, however, the need for power factor improvement and gradual speed-change, which may entail at times the use of a.c. commutator machines.

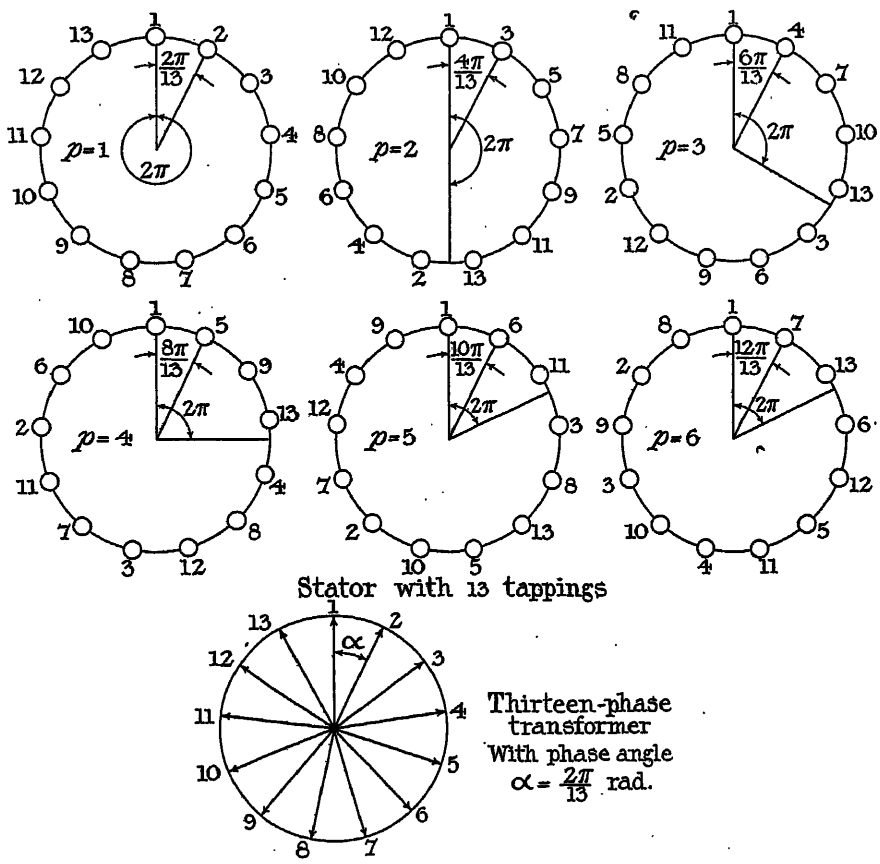

FIG. A.

Mr. H. Jack: In this country, due to the large number of relatively small power companies, the pro-

portion of d.c. to a.c. motors has always been higher than in the majority of other countries. The tendency is, however, for the proportion of a.c. motors to increase considerably, and the need for a good variable-speed a.c. motor has become extremely important. It is generally admitted by designers that a motor with the simplicity and the possible speeds of the d.c. shunt motor would meet the market requirements. The fact that the d.c. motor has a commutator is not now considered a serious defect. In addition to comparing the motor described in the paper with the variable-speed d.c. motor, it is also possible to examine how far it meets the actual practical requirements of a variable-speed a.c. motor and to compare it with other multi-speed and variable-speed motors on the market, such as the ordinary change-pole motor and the a.c. commutator motor. For the past 15 or 20 years we have had 2-, 3- and 4-speed change-pole multi-speed a.c. motors. These motors have been robust and comparatively cheap, yet they have not met the requirements of a variable-speed motor. By adding a phase converter and an elaborate controller, the author has again given us a multi-speed rather than a variable-speed motor. The sum of the whole matter is, therefore, that in some cases two additional speeds can be obtained by the author's motor, as compared with the change-pole motors previously available. Considering that the 2-, 3- and 4-speed change-pole motors have failed to meet the requirements, I think that the number of cases in which the motor described in the lecture will come any nearer the requirements is extremely limited, as it still has practically all the defects of other multi-speed change-pole motors. The speeds available are too limited. For example, on 25 periods there is no speed between 1 500 r.p.m. and 750 r.p.m., and the next speed is 500 r.p.m. Hence, on a motor with a 2 : 1 speed-range there are only three available speeds. If the maximum speed is chosen as 750 r.p.m. there are still only three available speeds on a speed-range of 750 to 375 r.p.m. On 40 periods there is no speed between 1 200 r.p.m. and 800 r.p.m., and the next possible speed is 600 r.p.m., and similarly on 50 periods there are no possible speeds between 1 500, 1 000 and 750 r.p.m. Further, the current-rush on changing from one speed to another is excessive unless the additional complication of inserting resistance in the primary circuit before changing to the next speed and then cutting it out again, is introduced. Also, the power factor on the lower speeds is very poor and the air-gap may be reduced unduly in order to improve this power factor. Consider now the a.c. commutator motor which has been developed during the past few years. We have the series type and the shunt type. The former is suitable only where the load is constant at each speed, and thus meets only a limited number of requirements. The shunt type should be more correctly called the type having a characteristic similar to the d.c. shunt motor. The motor is made in this country, and the increasing demand shows that it is meeting the requirements for a true variable-speed a.c. motor comparable with the d.c. shunt motor. Its construction is simple, and the commutator requires to deal with only a small proportion of the power of the motor. It is usually constructed for speed-ranges of 3 : 1, but for sizes below 100 h.p. considerably greater speed-ranges can be given, and in this respect the motor is actually superior to the d.c. shunt motor. The important point, however, is that between the lowest speed and the highest speed any desired speed can be obtained, and this cannot be obtained with the change-pole motor. The a.c. commutator motor is even superior to the d.c. shunt motor in this respect, as the speeds of the d.c. motor are dependent on the grading of the field rheostat, whereas the a.c. motor gives the equivalent of a d.c. motor with an infinite number of rheostat contacts between the limits of the speed-range. Further, no rheostat or controller is necessary with the a.c. commutator motor, and it is only necessary to provide a starting switch. The starting current is about equal to full-load current and the starting torque is from one to two times full-load torque. Further, by the insertion of resistance it is possible to get extremely low crawling speeds, and at these speeds the motor is far more stable than the ordinary induction motor. The power factor at the higher speeds is unity, or even leading, and can be maintained at a high value at fractional loads. At low speeds the power factor can also be maintained at a fairly high value. These features of the a.c. commutator motor are sufficient to show that in it we have a motor equal to the d.c. shunt motor and capable of meeting all the requirements for sizes up to from 150 to 300 h.p., according to the speed-range and the frequency. The a.c. commutator motor has not yet been developed to the sizes required for large rolling-mill work, but the multi-speed change-pole motor is quite unsuitable for large reversing rolling mills or modern continuous mills. For the latest type of continuous mill, several of which have been recently installed in this country, the demand is again for a large number of speeds of the order of 17 to 31, and the powers are as large as 4 000 h.p. Such requirements with an a.c. supply are best met by the induction motor working in series with an a.c. commutator motor of the Scherbius type. For small speed-ranges the speed is varied from synchronism downwards, and for larger speed-ranges the speed is varied both above and below synchronous speed. Apart from rolling mills and similar heavy duty, variable-speed motors are required mainly for paper making, paper printing, reciprocating pumps, compressors, fans, calenders for paper and textiles, rubber manufacture, stokers, machine tools and certain special textile work such as calico printing and cotton spinning. The different speeds are demanded by the variation in the class of work with the same machine, and, in addition, the variation of the quality of the materials with the same class of work. The variation in the class of work demands a large speed-range and as large a number of speeds as possible in that range. A variation in the quality of the material demands a temporary or occasional slight change in speed from the customary speed for that work. It is evident, therefore, that, with the exception of large rolling-mill work and other heavy duty, the variable-speed a.c. commutator motor with the shunt-type characteristic and its gradual change from one speed to another, fulfils the requirements of industry for medium-

to small-size variable-speed a.c. motors far better than any change-pole motor.

[Mr. Creedy's reply to this discussion will be found on page 333.]

North Midland Centre, at Leeds, 9 January, 1923.

Mr. J. C. B. Ingleby: In connection with Fig. 17 I do not quite understand which peaks are supposed to represent the five speeds for the 8, 10, 12, 14, and 16-pole machines, or why the lower no-load currents fall so considerably. Can the author say why, for any given speed shown in Fig. 22, the leakages differ? For instance, taking the 10-pole machine, the leakage is 1·1 on the top curve and 1·82 on the bottom. Referring to the curve of costs shown on the slide, it appears that the difference in price compared with the slip-ring motor varies from 50 per cent to 100 per cent. Does that increase of cost include a starter and transformer, or is it for the motor only? The author's motors will effect a great saving in copper, and it should be commercially practicable to put them on the market.

Mr. W. B. Woodhouse: It would, I think, be useful to have a comparison of this particular type of motor with the other alternating-current motors that may be used. First, in respect of the efficiency at different speeds, if the author could give, for example, the relative efficiencies, at various speeds, of a Creedy motor as compared with a slip-ring motor, where the speed regulation is obtained by resistance in the rotor, and as compared with any recognized type of commutator motor, I think that the advantage of the Creedy motor would be more evident. It is a great advantage to have a stable speed which is some percentage of the highest speed. Where the speed of a slip-ring motor is regulated by rotor resistance, one remembers that the speed is not stable if the load varies. I think it would be useful also if we could have a similar comparison for the torques of these different types of machine at different speeds. A machine in which the torque varies with the speed may suit one purpose. In other cases constant torque at all speeds is wanted, or the highest torque is required at the lowest speed. The second half of the lecture dealing with the cascade synchronous motor is particularly interesting to a supply engineer; it seems that we have at last got a motor which not only does not draw any magnetizing current from the line but actually returns some.

[Mr. Creedy's reply to this discussion will be found on page 333.]

South Midland Centre, at Birmingham, 10 January, 1923.

Mr. R. A. Chattock: The introduction of a reliable and simple alternating-current motor having variable-speed characteristics would go far to eliminate the necessity for using direct current for many purposes. The author's description of the multi-speed cascade motor appears to cover all the requirements under ordinary working conditions, and the only questions to decide are whether this type of machine has been run in commercial service sufficiently long to show that it is reliable, and whether the large number of terminals and connections involved proves to be a source of weakness. I should be glad if the author would give some information on this point. The description of the variable-speed induction motor makes it clear that in order to change the speed it is necessary to break the main circuit. I consider that this would prove a disadvantage under many conditions of service. I should also like to know how this interruption of the circuit affects the variable-speed synchronous induction motor, because it seems to me that when the circuit of a synchronous motor is interrupted, it will at once fall out of step and will have to be re-synchronized. Such an operation would in most cases prove to be quite unworkable in practice. From Fig. 21 it appears that the power factor of the variable-speed induction motor is poor compared with that of the ordinary induction motor, and this is especially so at low speeds. This, of course, adversely affects the system of the undertaking supplying the power. I should like to know whether the phase converter to which the author referred as being necessary in connection with the variable-speed induction motor, still further reduces the power factor below the values given in Fig. 21. Has the author tried using condensers or power-factor correctors in connection with these motors, and if so, with what result?

Dr. M. L. Kahn: The lecture shows what able and ingenious engineers can do if they set out to satisfy a long-standing demand for special features of machinery, which has hitherto not been met. The author himself appears to recognize the limitation of his invention and states the various cases where a commutator motor is preferable to his propositions. The inherent limitation of his motors is the fact that only a limited number of speeds with rather big steps can be supplied. The limits of 19 r.p.m. and 21 r.p.m. compared with 20 r.p.m. mentioned in the lecture in connection with this point are rather optimistic. As Fig. 21 shows, the step may be 20 to 30 per cent for the most favourable and, incidentally, very costly arrangement, to from 30 to 50 per cent in ordinary cases. Even this is, however, a great advance on the old pole-changing methods where, with one winding only, a speed-ratio of 1 to 2, or 100 per cent stepping, could be obtained. In explaining his winding the author starts from the ring winding with a number of tappings for various numbers of poles, and mentions that similar results could be obtained with a lap-wound drum winding. He does not mention how his winding is arranged. Are we to take it that he also uses lap-wound drum windings in his machines? If so, how is the difficulty of the pole-span of the coils overcome? Normally, coils are wound with a coil-span of

about one pole-pitch. They may be lengthened or shortened up to 33 per cent without the output of the machine being materially affected. This means that a winding with a span corresponding to a pole-pitch of 8 poles can be used for 6 poles or 10 poles. For 6 poles the pitch is 0·75 times full pitch and for 10 poles 1·25 times. If, however, the same winding is to be used for a speed-range of 428/1 000, i.e. for 6 poles and 14 poles, as mentioned on page 316, it would, if wound for a mean pitch, have a span differing by 40 per cent from the normal value of the two limits of the speed-range. This will tend to reduce the output obtainable from a given size of machine for the extreme limits of the speed-range. The proposed method of pole-changing involves a motor with a large number of connections, leads and terminals, a phase transformer with similar leads and terminals, complicated switch-gear and a starting resistance or auto-transformer. These complications can be justified only in cases where speed variation is absolutely necessary. The claim of increased starting torque for squirrel-cage motors of this pattern can only relate to such cases. The motor cannot supersede the standard slip-ring motor on the plea that it dispenses with slip-rings, while giving at the same time a large starting torque. The complications introduced by the gear and the increased possibility of breakdowns, apart from the question of first cost, far outweigh the advantage of doing away with slip-rings.

Mr. G. M. Harvey: I have recently seen some test sheets concerning 10-h.p. single-speed Hunt cascade motors running at 500 r.p.m., and I note that the power factor obtained upon full load is only 0·74. We have at the University a two-speed cascade motor giving 10 h.p. at 750 r.p.m. (8 poles) and 6·6 h.p. at 500 r.p.m. (12 poles); the power factors obtained upon test with this motor at full load are 0·86 at the top speed and 0·68 at the lower speed. These figures do not at all agree with those claimed by the makers in some of the earlier papers describing this motor, and I recollect a description of a 300-b.h.p. motor running at 360 r.p.m. with a power factor of 0·92, and giving 200 b.h.p. at 250 r.p.m. with a power factor of 0·9. I should be glad if the author would explain the discrepancy between these figures. I have also noticed in the motor at the University a tendency to stick in the top speed when an attempt is made to reduce to the lower speed by opening the rotor circuit and closing the tapping controller. Can the author explain this? I am greatly in favour of the cascade motor for mining, and I should be glad if the author would indicate where a simple explanation of the windings of the Hunt cascade motor is to be found. The advantages of the cascade motor for mining work are as follows: The even torque obtained at "crawling" speeds is of great advantage for haulage work, as it prevents "snatching" at the rope. The starting characteristics of a slip-ring motor are obtained without the danger and inconvenience of the use of slip-rings, and a low-speed motor is obtained which compares very favourably in bulk with a plain induction motor running at the same speed. In this connection it seems to me that the advantage claimed by the author for recent improvements which enable the cascade motor to be run at 1 000 r.p.m. are illusory, since the chief advantage is the exceedingly low speed which can be obtained with a reasonable efficiency.

Mr. F. W. Close: I appreciate the ingenious way in which the author has made possible the simplification of the control gear by reducing the number of connections which have to be interchanged for the respective speeds. It may be thought that the time required to make the necessary changes in interconnections between the supply, motor and transformer of a six-speed set would be somewhat lengthy, and so allow the motor appreciably to fall in speed during the change period; but, taking the controller illustrated in Fig. 15, the total time for a change-over on that controller from one speed combination to the next is practically determined by the natural speed at which the contactors will open and reclose, and it is found that the change can be made in something like $\frac{1}{2}$ second, which is about one-quarter the time mentioned by the author. This period of time is an important consideration as, during a part of the time taken to change over, the supply is cut off from the motor, and the latter will therefore commence to fall in speed. With regard to the control of a machine tool driven by a three-speed motor, and the quite reasonable fear expressed that the operator may move the handle in anything but an ideal manner, I have seen in operation the three-speed motor and the controller which the author exhibited. The motor was connected by belt to another machine, and the controller handle was rotated rapidly from the "off" to the "full speed" position, and then back again many times in rapid succession, without pausing in the intermediate steps. No trouble arose, the only thing to be noted being the squealing of the belt due to the rapid acceleration produced by the torque exerted.

Mr. W. J. Line: In the lecture the author's multi-speed system is shown applied to polyphase motors. Judging by his silence on the point, he has not entertained the possibility of applying it to single-phase induction motors, or, at any rate, motors running off single-phase supplies, and proposes to abandon this case to the single-phase commutator type. As the elimination of the commutator is admittedly an advantage, giving

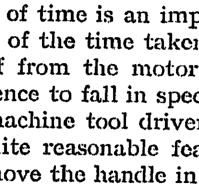

FIG. B.

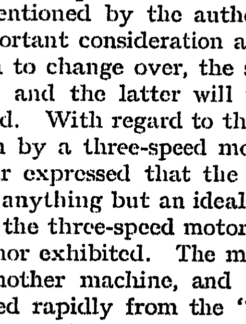

FIG. C.

a simpler and more robust machine, I have a suggestion to make which might enable the advantages of the author's system to be obtained on single-phase supplies also, and the same principle developed on polyphase supplies might enable the transformer, which the author finds necessary, to be replaced by other apparatus which might be cheaper. Consider first the single-phase induction motor running on single-phase mains. The mains and the stator winding may be

represented as in Fig. B. For starting, another winding is provided which, either due to its own additional reactance or to a separate choking coil, carries current out of phase with that in the other winding, producing a rotating field instead of an oscillating one (see Fig. C). The same result might be obtained by a condenser in one of the windings, and we might advantageously combine the two, thus causing the current to lead in one winding and lag in the other

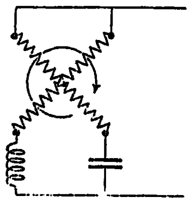

FIG. D.

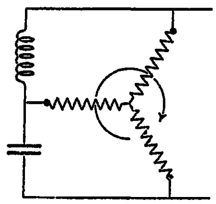

FIG. E.

(see Fig. D). If this were made a permanent running arrangement, a two-phase motor could be run off a single-phase supply. On similar principles a three-phase motor could be run off a single-phase supply as shown in Fig. E, and this arrangement has been used, under certain circumstances, on the Continent. We can add a second three-phase star winding on the same motor, and thus obtain a *six-phase* machine running off a single-phase supply (see Fig. F). The same may

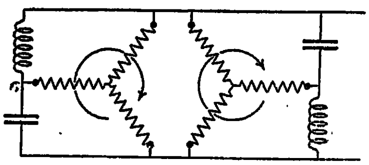

FIG. F.

be represented in mesh connection, as shown in Fig. G. By connecting those phases which are at 180° with one another, in series and mutually reversed, the number of terminals may be halved, while the machine remains six-phase, and a second speed, double or half the other, might be obtained by the author's methods. Let us now consider motors on three-phase supplies. A six-phase star-connected motor may be run off a three-phase supply (see Fig. H) or in mesh form (see Fig. J), and a nine-phase mesh-connected motor may be run off a three-phase supply in a similar manner, as shown in Fig. K. An arrangement has now been arrived at in which the arrangement of stator winding with 9 terminals, shown in Fig. 7 of the paper, might be utilized. In place of the special transformers required to supply such a winding, three condensers and three choking coils would be required, but the author's switching arrangements would remain un-

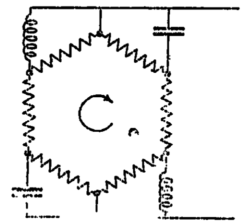

FIG. G.

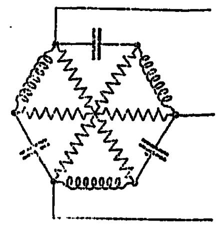

FIG. H.

altered. The question then arises as to whether the condensers and choking coils would be cheaper than the transformer and equally good. Has the author made any experiments in this direction? It is true, as

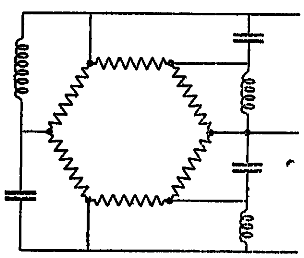

FIG. J.

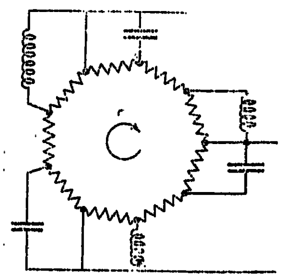

FIG. K.

stated in his verbal reply to the discussion, that the leading and lagging effect would not be constant at all loads. Means might, however, be found to overcome this difficulty if the arrangement proved worth while on the score of cost. This point seems worthy of investigation.

[Mr. Creedy's reply to this discussion will be found on page 333.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 22 JANUARY, 1923.

Mr. F. H. Downie: The author has given a most interesting account of a new development in induction motors, which will have many applications in practice. Can he give some information about the variation in the breadth factor with the different numbers of poles? In the existing two-speed windings of Lindström, for example, the breadth factor is 0·95 for the larger number of poles and 0·7 for the smaller number, showing that the winding is not equally efficient in both cases. I should like to know if a similar result is found in the case of the windings described in the lecture. Usually these windings for different numbers of poles show harmonics in the field distribution curve, the seventh especially reaching high values which produce a tendency for the motor to crawl at one-seventh synchronous speed when a squirrel-cage motor is started. Has the author found similar effects in motors with the winding described? Are there any limitations to the possible numbers of poles for which a motor can be wound? In other words, would it be possible to wind a motor for 20, 22, 24, 26, 28 and 30 poles, thus giving 6 speeds covering a range from 300 r.p.m. to 200 r.p.m. with a 50-period supply? Fig. 18 leads me to expect that the ratio of maximum torque to normal torque varies with the number of poles. Is it possible to design a motor to have a good power factor and efficiency at

all speeds and at the same time a ratio of maximum torque to normal torque of at least 2 at all speeds? The author mentions that in Fig. 18 the torque represented by 1 mm is proportional to the number of poles, and from this I gather that the maximum flux density in the gap is constant at all speeds. I should like the author to confirm this. I think that the polyphase commutator motor has a greater field of usefulness than the author would leave to it, and that for small outputs it would in many cases be cheaper and better to use a commutator motor than a variable-speed induction motor.

Mr. J. W. Jackson: From my early experience with this particular type of motor plant I found that I was developing bias against it because of its apparent unreliability. This, however, I afterwards found to be not so much a charge to be levelled against the technical arrangements of the equipment, or even the manner in which it had been manufactured, but rather the commercial arrangements of the manufacturer were at fault in dealing with the breakdowns when they did occur. Breakdowns are bad enough, but when added to these there is a serious difficulty in effecting repairs, no one can wonder at a plant gaining a bad reputation. I should like the author to explain why the motor takes a greater amount of current when running at its lowest speed and no load, than it does when it is running at its highest speed and no load. Is this low-speed arrangement secured at the expense of power factor? During the past two years I have had personal experience with motors having four-speed and six-speed arrangements, one of these being of the earliest pattern and fitted with the popularly described "piano" type of controller. All these have been remarkably free from trouble. It would appear from the lecture that the cascade type of motor would very quickly repay the increased capital cost over a fixed-speed motor when applied to air compressors, from which very frequently a small amount of work is required. When the fixed-speed motor is fitted, a large percentage of the full power is used on the compressor even when it is delivering a small amount of power, thus giving an extremely low efficiency, or, in other words, increasing very considerably the power costs for air-compressing. There is apparently a strong feeling that the cascade motor is not as reliable in operation as a fixed-speed motor, and when added to that idea of unreliability is that of the considerably increased capital cost, it is not surprising that the fixed-speed motor is installed.

Mr. A. T. Robertson: There is a great deal that requires explanation before the subject can be clearly understood, particularly in regard to the details of the windings employed; for instance, no indication is given by the author as to how he obtains the equivalent of the ring winding with a winding of the usual drum type. Is it correct to assume that the drum winding used has such a pitch as to give the smallest number of poles required in any particular case? Where only two-phase supply is available does the author propose to convert this by means of the phase transformers to the same number of phases as would be used if three-phase supply were available, and so use similar machines for both two-phase and three-phase supply? There will not be the same possibility of convenient speed-ranges on 40 and 25 periods as given in the lecture for 50 periods, and it would appear that commutator motors might be necessary, particularly on 25 periods, whereas a pole-changing motor could be used on 50 periods. On page 315 it is stated that the size of the phase transformer may be reduced from 30–40 per cent of the size of a voltage transformer for the same power, to 18–20 per cent when using the factor 0·75; these figures appear, however, to require some modification. The analogy of the automobile gear is most unfortunate, as the whole point is that a constant-torque, not constant-power, electric motor is being considered, whereas the automobile engine is a constant-power unit, the gear being used to obtain higher torques at low speeds. Direct drive on top gear is used, so that the most efficient drive is obtained for normal running.

Mr. C. Turnbull: We are the more indebted to the author in that the information given in the lecture might prevent him from taking out a valuable patent later. The day may come when Parliament will realize that the penalizing of inventors by annulling a patent on the plea that the idea was more or less vaguely foreshadowed in a scientific paper, is not beneficial to the nation. The difficulty with variable-speed motors is that the variations required do not always fit in with those obtainable by the author's methods. Are the motors in question suitable for printing-machines, lifts and organ blowers?

Professor W. M. Thornton: Is there any upper or lower limit to the sizes of the motors? For example, could one use them efficiently up to 10 000 h.p. for rolling mills, and as low as 1 h.p. for organ-blowing? Is there a size in which the efficiency of construction and operation is a maximum, due regard being paid to cost?

The Author's Reply to the Discussion at London, Leeds, Birmingham and Newcastle.

Mr. F. Creedy (*in reply*): I have to thank Mr. Hunt for his very clear exposition of the principles of the multi-speed winding described in Part I of the lecture, and its relation to both the old and the new cascade windings. I am quite in accordance with his views. The data which he gives of the relative d.c. and a.c. ampere-turns on the synchronous cascade motor, and also those relating to large ship-propulsion motors, are very interesting. I myself have found it necessary to use three groups of coils per pole instead of three groups per pole pair in designing such a multi-speed motor as he refers to, and have found a similar improvement in its properties.

I have also to thank Dr. Smith for his alternative statement of the principles involved. All such alternatives are of value, as one view point may appeal more than another to any given individual.

Mr. Jack, in his remarks, has scarcely been fair to

alternative types of apparatus. It is quite true that for the past 15 or 20 years it has been possible on known principles to build 2-, 3- or 4-speed change-pole motors, but Mr. Jack does not point out that a 2-speed motor, if with a single winding, could only have speeds in the ratio of 2–1, that is, 100 per cent stepping. To obtain anything better than this, two distinct windings must be employed. The disadvantages of such windings are very great in many cases, as they involve a much larger frame size, very much impaired ventilation, and much greater magnetic leakage. If I were to permit myself the use of two windings in this manner, I could obtain a 12-speed motor with a speed stepping of 10–15 per cent. Without using the two windings and employing a type of design which permits us to obtain, from a given frame size, about 85 per cent of the output given by a single-speed motor, a step of 20 per cent in the most favourable case and 30 per cent in ordinary cases can be obtained, as pointed out by Dr. Kahn in the discussion at Birmingham.

It does not appear to be sufficiently realized that in these multi-speed motors any combination of numbers of poles can be obtained whenever it is worth while to do so, and, while dealing with this point, I may reply to Mr. Downie's remarks on the same subject in the Newcastle discussion. It would be quite possible to obtain such a combination as 20–22–24–26–28–30 poles in large machines. It would involve a 3–24 phase transformer and controller similar to that shown in Fig. 15, but having 12 instead of 9 switches on each vertical shaft.

Another difficulty of the old multi-speed motor was the practical impossibility of building it with slip-ring control. This difficulty also has been remedied by the new winding, thus adding very much to the field of application of the machine.

Mr. Jack does not, I think, improve his case by complaining that there are no speeds available from 1 500 r.p.m. to 750 r.p.m. on 25 periods. Small 25-period motors certainly offer a better case for the commutator machine than on any other frequency, although, even here, machines of the multi-speed type running at speeds of 750/500/375 have been used with success down to fairly small sizes. Probably more motors have been built for 40 periods than for any other frequency, and there can be no question that the machine forms a very useful piece of apparatus at this frequency.

The power factor of the machine is discussed in connection with remarks made by other speakers.

I do not, of course, claim that the multi-speed machine is the only type of variable-speed apparatus that should ever be used, and this is, I believe, made sufficiently clear in the lecture. On the contrary, it is this very attitude that I protest against, namely, that of making a hobby of a particular type of apparatus and trying to apply it whether or not it is the most suitable for the purpose. If in any given case the commutator machine is really the best, I hope I shall be the first to recommend it. On the one hand, for instance, we have the continuously variable speed, which is certainly a very strong point, while on the other we have to content ourselves with speed-steps of the order mentioned above.

By means of these speed-steps we can in any given case get within 10 per cent or, at the most 15 per cent, of the speeds desired. For instance, supposing we wish to obtain a speed of 875 r.p.m., the nearest we can obtain is either 1 000 or 750 r.p.m., each of which differs from the speed required by $12\frac{1}{2}$ per cent. We have first to settle, therefore, whether a speed variation of $12\frac{1}{2}$ per cent from the ideal value causes any serious detriment. Next, we have the lower efficiency of the commutator machine, amounting to approximately 10 per cent, as may be seen by reference to Mr. Teago's paper,* which shows that the efficiency of a 10 h.p. motor does not exceed 80 per cent, as against well over 90 per cent in the case of an induction motor. The effect of this on running costs cannot be ignored. For instance, in a 25 h.p. motor running 8 hours a day and $5\frac{1}{2}$ days a week, a machine with 90 per cent efficiency takes 1 000 units less a quarter than the machine with only 80 per cent efficiency. On the other hand, it is only fair to say that the commutator motor on some of its speeds, though not all, gives a better power factor than the induction motor. This may somewhat offset the lower efficiency in cases where a system of charging is adopted which takes account of the power factor.

Having settled these two points, we have next to consider whether the motor can be built to give the speed-range desired. Owing to the requirements of commutation, the flux per pole of a variable-speed commutator motor is strictly limited, and consequently motors of considerable size must have a large number of poles, i.e. they must be built for a low speed. The multi-speed type of motor is not subject to any such limitation and can, on the contrary, be built for nearly any speed-range desired on normal frequencies, although, as stated above, the case for the commutator machine is certainly improved on 25 periods.

I quite agree with Mr. Jack that the modern a.c. commutator motor can be built so as to be free from commutator and brush troubles. Another point which really cannot be lost sight of is that of first cost, to which he makes no allusion at all. In large horse-powers, owing to the necessarily very low speed of the motor and its extremely large commutator, this cost must be very high, and it is just here that the multi-speed motor shows to such advantage, since it can be built for almost any speed. The greater the size, the smaller in comparison is the cost of the switchgear. In small sizes the commutator motor is more favourable, while the switchgear of the multi-speed type tends to become expensive relative to the machine itself. Hence, we are practically restricted to the simpler three- or four-speed types below, say, 10 h.p.

Fig. 14 shows the relative costs of the multi-speed motor and it would be interesting if, on some other occasion, a similar curve relating to the commutator motor could be published. In some cases I am aware that the advantages of the continuous speed-range are so great that all the above questions must be answered in favour of the commutator machine.

With regard to the use of multi-speed motors for rolling mills, I have devoted a good deal of attention

* *Journal I.E.E.*, 1922, vol. 60, p. 328.

to this subject also, and a type of motor is now being considered in which an absolutely gradual speed variation can be obtained entirely without the use of commutating machinery. I hope to be able to publish further particulars of this on a future occasion.

Confining ourselves to familiar apparatus, however, it is well known that the size of a cascade commutator set of the Scherbius or Kramer type such as those advocated by Mr. Jack is proportional to the difference between the speed of the main induction motor and its synchronous speed. If, therefore, we can use a multi-speed motor such as that shown in Fig. 7, which is capable of giving, say, three speeds with slip-ring control on each, we can reduce the size of the auxiliary set to a mere fraction of that required if the main motor is of the single-speed type. Hence, even where continuous speed variation is required, the multi-speed motor enables us to effect great economies. In point of fact, in merchant mills, where speed-change is required principally when changing the section to be rolled, continuous speed variation is in no way necessary, and the multi-speed motor as described in the lecture is by far the most economical apparatus that can be installed, both as regards first cost and cost of operation.

In view of the examples of rolling-mill motors now actually in operation and referred to in the lecture, I cannot understand how Mr. Jack can assert that these machines are not suitable for rolling-mill work.

In replying to Mr. Chattock's remarks in regard to power factor, I propose to deal with those of other speakers on the same subject. The full-load power factor of the machine varies, being on top speed quite as high as, or in some cases higher than, in the best induction motors, owing to the multi-speed motor having a far greater number of phases per pole than the ordinary three-phase motor, which leads to a wave-form approaching a sine type much more closely than in the latter. This is dealt with more fully below. The power factor falls off as the speed decreases, due to the reduced horse-power output of the motor. The amount of wattless current absorbed by the machine is, however, practically constant and it is this, and not the power factor directly, which is of interest.

A multi-speed motor giving 100 h.p. on its top speed and therefore rated as a 100 h.p. motor will take practically the same amount of wattless current as a 100 h.p. motor arranged for one speed only. When it is only giving 50 h.p., due to the reduction of speed to one-half, it still continues to absorb the same wattless current, and consequently gives the same power factor as a 100 h.p. single-speed motor when running on half load.

Dealing with the question of phase compensation, it has not yet been found possible to apply phase compensation on this type of motor on more than one of its speeds. As mentioned in the lecture, it can be made to operate as a synchronous motor on two speeds, but arrangements having a suitable degree of simplicity have not been developed on these lines for more than two, or possibly three, speeds.

It may here be stated that these multi-speed synchronous motors are self-synchronizing on each speed. Some machines have been built which will synchronize themselves when switched in at a speed of 10 per cent below synchronism, although this is, of course, not recommended, but no difficulty whatever is experienced if the machine is allowed to run up as an induction machine and the exciter circuit then closed.

Due to the fact that the amount of wattless current taken on all speeds is practically the same, however, the static condenser presents an ideal method of raising the power factor of such a set to unity, and, wherever this requirement is met, it is usual to connect the static condenser in parallel with the set, when it will raise the power factor to unity on every speed, and not on one only, and keep it above 0·95 on practically every load.

In reply to Dr. Kahn, Mr. Downie and Mr. Robertson, I have apparently not succeeded in explaining sufficiently clearly how it is that a lap-wound drum winding can be used instead of a ring winding. Fig. L shows three sketches of a drum-wound coil lying (*a*) in a field of six poles, (*b*) in a field of 10 poles and (*c*) in a field of

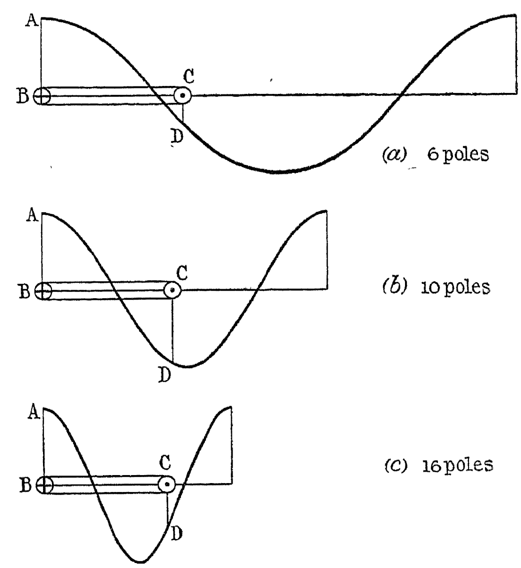

FIG. L.

16 poles, the pitch of the coil being approximately one-tenth of the circumference. The sine curve shown in the figure may be taken to represent the values of the air-gap density at a particular instant and, if so, the ordinate AB to the curve will represent on a suitable scale the voltage induced in the left-hand conductor. Similarly, the ordinate CD represents that induced in the right-hand conductor. The curves have in every case been so drawn that the left-hand conductor lies at the point of maximum density. The total E.M.F. induced in the coil will in each case be (AB + CD). It will be seen that in curve (*b*) (Fig. L), representing the 10-pole condition, the E.M.F. induced in the coil is a maximum, since CD as well as AB is a maximum. In the curve corresponding to six poles, the pitch of the coil is considerably less than the pole-pitch and, therefore, CD is a good deal less than AB, but nevertheless the sum of the two is only reduced to about 70 per cent of its previous value. Similarly, in curve (*c*), representing 16 poles, the pitch of the coil is a good deal more

than the pole-pitch and therefore CD is again reduced, but again the sum of AB and CD is only about 70 per cent of its full value. It is, in fact, in order to prevent too great a difference between the pitch of the coil and the pole-pitch, that it is usual to limit the speed-range of these motors to a value not exceeding 3–1.

I should like here to clear up a slight misunderstanding into which several speakers appear to have fallen. It is only the cascade machine that I consider to be suitable for use as a single-speed machine, and I agree perfectly with Dr. Kahn that the control gear required with the multi-speed machine is too elaborate to allow it to be used as a one-speed machine.

In reply to Mr. Harvey, I am not sufficiently conversant with the history of the cascade motor to enable me to answer his remarks as regards the machines of which he has had experience, as it is only comparatively recently that I have become connected with this type of machine.

It is a normal characteristic of the cascade motor as hitherto built, that if brought up to its top speed by any means, as, for instance, by the short-circuiting of the slip-rings, it will continue to run at that speed, notwithstanding the fact that the slip-rings are again open-circuited. This is also true of the cascade set, for instance the set shown in Fig. 23. If the first machine is brought up to its synchronous speed, 1 000 r.p.m., the rotor frequency is reduced to zero or, at most, $\frac{1}{2}$ period per second. At such a frequency as this practically no voltage will be induced in the secondary of the second machine, which accordingly carries little or no current. The primary at a frequency of $\frac{1}{2}$ period has extremely little inductance and acts almost purely as a resistance in series with the slip-rings of the main motor. This is, I think, the explanation of the characteristic noticed by Mr. Harvey, which is common to all cascade apparatus whether internally or externally cascaded.

I regret to say there is really no elementary exposition of the principles of the internal cascade motor, and I can only refer once again to my previous paper.* Mr. Harvey states that for mining work the low-speed cascade motor meets all requirements, but the properties of the cascade motor are available far beyond the mining field and it is in this extended field that high-speed motors show to their greatest advantage.

It is largely due to Mr. Close's design of controller, namely, that shown in Fig. 15, that this type of machine, at any rate in the larger sizes, has assumed a practical form. Other types of controller have been used, notably one which became popularly known as the "piano" type and which is referred to by another speaker, but it was not until the controller shown in Fig. 15 was designed that I felt that all the problems had been really solved. Mr. Close's confirmation of my statements in regard to the time required to change speed with the type of controller shown in Fig. 15 is very welcome. This should be sufficient to answer Mr. Chattock's inquiry as regards any possible difficulty due to this case. In none of the considerable number of these machines which have been placed in service, many of them starting and changing speed under

* *Journal I.E.E.*, 1921, vol. 59, p. 511.

full load, has any difficulty of this nature been experienced.

In reply to Mr. Line, I have not considered it desirable to use these multi-speed motors on single-phase circuits. I hold rather strong views on this subject, although the present is not the place to enlarge on them, and I believe that the single-phase induction motor is at the present moment entirely obsolete and that within a very few years it will cease to be marketed, its place being completely taken by the commutator motor. Without discussing Mr. Line's various arrangements in detail, it seems to me that they would be vastly more expensive than the simple type of transformer which I employ.

Mr. Ingleby draws attention to a number of points in which the lecture is not perfectly clear. Dealing with these points in order, the point 1/2 in Fig. 17 marks

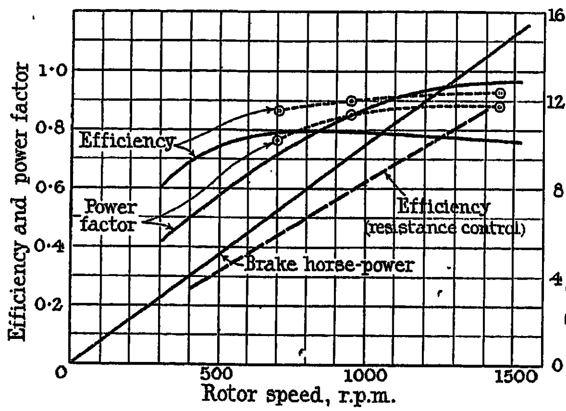

FIG. M.—Torque maintained constant while speed was varied by brush adjustment, by pole changing, or by altering rotor resistance.

a point at which the number of poles is changed from 16 to 14. The sequence of operations is as follows:—

Simultaneously with the change in the number of poles, the voltage is reduced by means of an auto-transformer tap on the controller, in order to reduce the current kick. This explains the reduction in the no-load current after the change in the number of poles. The second step in the controller, namely, that marked 2/3, restores the voltage to its normal value, and it will be seen that the no-load current shows a considerable rise. Similarly, the point marked 3/4 corresponds to the change from 14 to 12, 5/6 from 12 to 10 and 7/8 from 10 to 8. The leakage coefficients differ in the curve shown in Fig. 22, because these three curves relate to different machines.

The cost curve gives the ratio of costs between the slip-ring motor complete with its starting panel, circuit breaker, etc., and the multi-speed motor complete with its switchgear, circuit breaker and transformer (where necessary).

As requested by Mr. Woodhouse, I have included in Fig. M a curve showing the relative efficiencies of the multi-speed motor and the motor regulated by resistance control. Another curve shows the relative efficiencies of this motor compared with the Schrage

commutator type of motor, the efficiencies of the latter being taken from Mr. Teago's paper already referred to.

In reply to Mr. Downie in regard to harmonics, the number of sections per pole is greater than on a two-phase motor, even at the lowest speed. On the higher speeds, however, the number of sections per pole is far greater than in even the best types of three-phase motor, the consequence being that the wave-form on the higher speeds approaches the pure sine curve more closely than in any standard three-phase motor, the deviations from it amounting to less than 2 per cent, as shown by the diagram drawn after the manner explained by Hellmund.* This has a marked effect in improving the power factor and it is found that exceptionally high power factors are obtained on the higher speeds of these machines.

I have never noticed any tendency for the machine to crawl at one-seventh full-load speed. This is an extremely annoying tendency in the single-speed squirrel-cage motor, and while it might conceivably occur in a multi-speed motor connected for, say, its lowest speed, we have a ready means of eliminating it by merely switching the motor on to another speed, so that such a cause of trouble, should it occur, is by no means so serious with the multi-speed type.

It is quite true that the ratio of maximum torque to normal torque varies with the number of poles. I endeavour to allow a ratio of maximum to full-load torque of not less than 1·8 on the minimum speed, rising to about 3·5 on the top speed. Again, as mentioned above, where a motor is subjected to an exceptionally heavy load on one of its low speeds so that the slip is great and the danger of pulling-out considerable, it is quite easy to switch it on to the next higher speed; hence again we have resources which do not exist in the single-speed motor.

It is quite true also that the maximum flux density in the gap is approximately constant at all speeds. Mr. Jackson's remarks are very interesting, as coming from one who has large actual experience with this type of motor. As a matter of fact, the first machine of this type ever built, referred to on page 312, which had none of the later improvements, and therefore required a transformer having no less than 30 phases has, I believe, been under Mr. Jackson's care. This machine is fitted with the very elaborate "piano" type controller that he refers to, and when first installed it required a good deal of adjustment. Even these earlier elaborate motors have, however, now run for several years without, I believe, requiring any attention, and from the later ones containing the simplifications described in the paper which permit of the use of a drum-type controller, practically all the possible causes of weakness in the earliest type have been removed. These motors are used to operate mechanical stoker gear and are of the squirrel-cage type, being the smallest machines built to give the full six speeds. In order to obtain these results with a minimum of switchgear the motor is of the constant horse-power type, in which the flux is reduced as the speed is raised, more or less as in the d.c. machine. This involves a corresponding reduction of the magnetizing current, and this is the explanation of the high magnetizing current noticed by Mr. Jackson.

In the modern type the magnetizing current is practically constant at all speeds. I quite agree with Mr. Jackson that there is a great field for this type of machine in connection with air compressors, and automatic control gear is now being developed to enable them to be applied in this direction. Mr. Jackson's views as to the unreliability of the cascade motor seem to me to be quite unique, as my experience is that one of its strongest points is its extreme reliability owing to the very great simplicity of its construction.

In reply to Mr. Robertson, two-phase motors have not been worked out in quite the same fullness of detail as three-phase motors, but on two-phase supplies it is proposed to use as far as possible a special two-phase transformer and a winding with a different number of sections.

As regards the automobile gear, the point is not of great importance, as the analogy is only a very general one. I wished to point out that arrangements are made in the automobile to avoid using gears under the most severe conditions of working, and that I do the same. It is immaterial that the severest working conditions may appear under different circumstances in the two cases.

In reply to Mr. Turnbull, these motors can be readily applied both to printing-machines and lifts. As regards organ-blowers requiring only a 1 h.p. motor or so, I prefer the small commutator type of motor. An organ-blowing equipment can be regarded as an air-compressor plant in miniature, and we find this type of machine admirably adapted for slightly larger plant requiring from 3 h.p. to 5 h.p.

These machines have been designed up to 20 000 h.p. for ship propulsion, while the low limit of rating is about 2 h.p. to 3 h.p.

* *Transactions of the American Institute of Electrical Engineers*, 1908, vol. 27, pt. 2, p. 1373.

WORKS PRODUCTION.

By G. H. Nelson, Member.

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Summary.

During the past two years a great deal has been written about production problems. Some of these contributions to the subject have been penned by idealists, who claim, for instance, that such and such a shop lay-out is the first essential to successful production. Others emphasize that lack of production is caused by "ca' canny" amongst the workers. The bearing of these factors on production, or the lack of it, can be dealt with by efficient organization and management, and it is with the establishment of such a works organization that this paper will deal.

With a view to interesting all sections of the industry, the author has dealt with the subject on general lines, with particular reference in places to the manufacture of electrical machinery, the object being rather to outline a general policy that has been followed in works with which he has been associated, than to go into detail which may not be applicable to any other works, as, naturally, detail must be based on the equipment in a particular works and the design of the apparatus manufactured.

Introduction.

Those who are continually in close touch with the workers cannot but feel the great responsibility which falls on them in being obliged to discharge men due to shortage of work; and cases occur which bring home to one the necessity of doing everything possible that may influence an improvement in trade. One appreciates that it is not possible to remedy all the defects at once, but if each individual assists in his own particular sphere results will soon be obtained.

The present depression is due mainly to the following four causes:—

(1) Taxes, etc., direct and indirect (necessary to pay for the cost of the wastage of war), which caused higher prices of commodities.

(2) The effect of (1) on the *morale* of the workers, resulting in the forcing up of wages to meet increased prices.

(3) This in turn has caused a further rise in the prices of commodities with a view to meeting these taxes plus increased costs of production.

(4) The accumulative effect of (1), (2) and (3) producing rash speculation, in its very widest sense, and upsetting the whole basis of labour's wages, trading and economic standards.

The remedies are now being applied and everybody must suffer, more or less, in consequence. These come in the reverse order to the causes, thus:—

(1) Traders' rash speculation has been stopped by the limitation of credits.

(2) The cessation of speculators' orders for goods (for which there was no real money available to pay) causes a lack of work.

(3) This, in turn, necessitates economic adjustment of wages and also makes the worker realize that he must give a day's work for a day's pay in order to retain his employment.

(4) Lastly, we come back to the necessity for economy in every direction in order to provide funds to pay off the debt which caused the high taxation; and the liquidation of debt will in time cause taxes to fall.

The nations of the world are poorer, and the present conditions can only be improved by economizing generally and by producing the world's needs more economically and so, even with reduced available income, enabling goods which are necessities to be purchased.

The author fully appreciates that there are other matters (besides reduction of costs of production) that need attention, such as adjustment of exchanges, and the investigation into and reduction of heavy costs of distribution in many industries. These, however, will no doubt be dealt with in time. If every section, i.e. finance, manufacture, distribution and labour of all grades, does its best towards this rebuilding of the industrial world, we shall have nothing to fear in the future.

The particular problem with which the author proposes to deal is the basis of production of the best article in the shortest time, at the lowest price. It should be realized, however, that lowest cost does not necessarily mean lowest wages, but it certainly does entail the most economical method of production, by the joint efforts of both employer and employed.

Much has been said and written about so-called "ca' canny" amongst the workmen, but the author is of the opinion from experience that this can be eliminated by a management which looks for and removes the causes and does not simply complain about the results of "ca' canny."

The fundamental for the organization of economical production is co-operation. A shop with a good layout, manufacturing good designs, does not necessarily produce cheap and good articles. There must be the closest co-operation between all sections of the staff and workmen before any real success can be achieved. The basis of co-operation is naturally the human element in all branches of the organization, and the amount by which the ideal is approached is controlled by the results obtained by the weakest human link. This is funda-

mental, and the author personally considers it to be of first importance. For this reason it is referred to before dealing with questions of general organization. The heads of factories must first be students of human nature, so that in selecting men for executive positions they can satisfy themselves that these men, in addition to thoroughly understanding the technical and practical side of their respective appointments, can also select and lead their subordinates to co-operate with other sections or branches of the works.

The special problem of the manufacture of electrical apparatus is so complex that it really cannot be left to haphazard methods, for there is no apparatus made in which there is a greater variety of materials.

TABLE 1.

Chart of Number of Parts and Materials used on a Standard Design of Rotary Converter.

Description of materials	Number of separate parts used
Rolled hard shaft steel	1
Cast steel	17
Forged steel	3
Special low-carbon steel	1
Mild steel	93
Key steel	27
Electrical sheet steel (ordinary quality)	518
Black sheet steel	1 529
High-tensile steel wire	98
Spring steel	4
Copper-plated spring steel	48
Cast iron	38
Wrought iron	12
Phosphor bronze	2
Cast brass	100
Brass rod	47
Sheet brass	48
Lead	5
Bell-metal	6
Hard-drawn high-conductivity copper bar	270
Rolled copper bar and strip	557
Tinned copper strip	270
Sheet copper	132
Copper wire	6
Copper tube	10
Flexible cable	8
Carbon	72
Bakelized micarta	52
Bakelite	1
Fibre	186
Mica	1
Micanite	316
Fullerboard	18
Canvas hose	2
Hardwood	78
9 plywood	6
Sub-Total	4 582
Steel nuts, bolts, washers and rivets	1 248
Copper rivets	576
Total	6 406

TABLE 1—*continued.*

Insulation material.
5 different qualities or thicknesses of fullerboard.
2 different thicknesses of leather paper.
Fibre.
Torpedo cord.
Bare paper mica.
Micanite strip.
Enamelled rope.
3 different thicknesses of tape.
2 different thicknesses of empire tape.

Varnishes.
Mica-sticking varnish.
Clear insulating varnish.
Standard baking-coil varnish.
No. 2 black finishing varnish.
Grey enamel.
Shellac (of 3 different specific gravities).

Finish on castings.
Anti-corrosive paint.
Knife filler.
Leather filler.
Brush filler.
Coat of priming paint.
Coat of finishing paint.

Total number of separate parts used (not including nuts, bolts, washers or rivets)	= 4 582
Total number of different materials used	= 55

In addition to the various ferrous and non-ferrous metals, there are insulating materials, mica, paper, linen, cotton and silk in various forms, string, fibre, asbestos, etc., and numerous varnishes and solvents. These, it will be appreciated, involve the employment of all types of labour, skilled and semi-skilled, in many different trades. Table 1 gives a list of the materials and the number of parts used in a rotary converter.

To achieve success in the manufacture of machinery such as the above on anything like a large scale, the works organization should be subdivided into distinct sections, each section having clearly defined functions. From experience, a works sectionalized as follows has given eminently satisfactory results:—

(1) Design.
(2) Works Superintendence.
(3) Technical Process Department.
(4) Rate-Fixing and Mechanical Process Department.
(5) Production Department.
(6) Inspection Department.
(7) Costing Department.

Fig. 1 shows the relationship between these sections.

These divisions were arrived at in an endeavour to arrange for the efficient automatic application throughout a works of the knowledge and experience of specialists in each particular branch, all co-operating to get final economic manufacture. It is quite impossible to find a man versed in carrying out the detail of all these various branches, and the aim of all manufacturers should be to obtain the full benefit of accumulated specialized experience and to pass this down to the actual worker,

so that he can apply his manual effort and skill in the best way. The time is past when a technical business can be run by one man doing everything, including the buying, the works managing, the planning, the costing, etc., and general supervision. This was satisfactory in the past when competition was not keen and the margins of profit were much higher, and when technical knowledge was not developed as it is to-day.

The success in actual practice of introducing the system about to be described is shown by the following results :—

(1) The relation between the total value of the work in progress and the value of the monthly output of completed machines was reduced from 7 months to 4½, thus giving a very considerable saving in capital required and the interest on that surplus capital.

(2) The average time of manufacture of a certain size of machine was reduced from 22 weeks to 18 weeks, and that of other sizes relatively. This has since been facture of a particular product is drawn upon and embodied in the design, the best results cannot be obtained. No man can be an expert in every process and operation in the manufacture of a piece of electrical apparatus. Each particular branch of industry is a large proportion of a life's study, and in large and small works specialists in various directions exist, and it is in the interests of manufacturers to consult them and get their ideas embodied in the design, so that mistakes and delays are not experienced in the shops. The author once heard a remark that one could not expect the people in the works to know the technical details that the designer has in mind, and he is in entire agreement with this. It is important, however, that as much as possible of this information be imparted to the workers. Every effort should be made by designers and shop staff to apply this principle of co-operation in its broadest meaning, and make full use of the knowledge of experts in various shop problems.

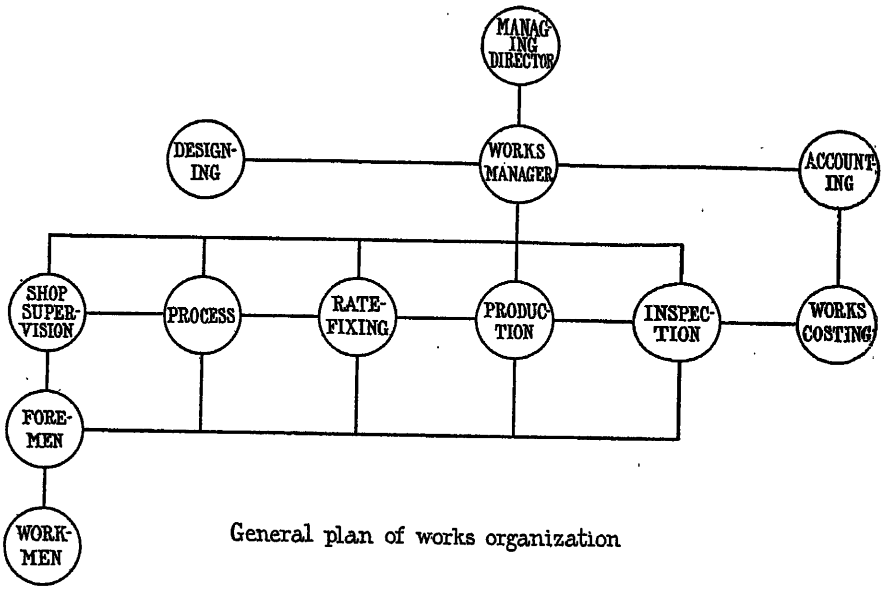


FIG. 1.

still further reduced, but this is accounted for by the fact that the shop is not now fully employed.

(3) The number of machines overdue was reduced two-thirds.

(4) The number of defects arising during manufacture on various operations has been reduced two-thirds.

(5) The accumulative effect has reduced the cost of manufacture by quite a considerable percentage.

The general lines of the system adopted in each of these sections which accomplished the above results will now be dealt with.

Design.

Under this particular heading the author must again take the opportunity of referring to the question of co-operation, for, in his opinion, unless the experience and knowledge of everybody concerned in the manu-

In this connection the author has one very good example in mind of an end bracket made from a 4-part pattern, with intermittent machining surfaces. The same bracket was re-designed for a 2-part pattern, with a consequent saving of 17½ per cent of the total factory cost, due to the simplification of machining and reduction of the number of scrap castings. If the co-operation of a foundry expert and machine expert had been solicited in the early stages, this design would never have been issued to the shop.

The author considers that a design of each part of a piece of apparatus should be considered at a meeting of the designer, the manufacturer and, if necessary, the salesman (who should know the requirements of purchasers) before it is finally put into manufacture, in order that the requirements of each party may be properly embodied.

Particular care should be taken to see that shop

drawings are clearly dimensioned and limits of accuracy given. Unmachined, rough machined and finished machined surfaces should be clearly marked.

Works Superintendence.

The most important consideration under this heading is that of labour. In order to handle this problem efficiently all those who have the handling of labour must be satisfied in their own minds that the biggest percentage of workmen are reasonable men, and, if this good percentage have rather distorted ideas on any particular subject, they should not be blamed but helped to change their distorted views. Problems looked at from their limited outlook can easily produce the conclusions at which they arrive. When these conclusions are wrong it is the duty of all employers of labour to endeavour to put before their employees both sides of the problem. The problem then often resolves itself largely into the elimination of selfishness from all parties, employers, employees and employees' unions. The author, personally, has the greatest respect and affection for the working classes as a whole, but he realizes that the vast majority are not in a position, through lack of knowledge, to consider the problems with which they are faced, and therefore simply accept the teachings of loquacious agitators.

(*a*) *Works education.*—The importance to all in industry, and to the nation as a whole, of improving the position is apparent to those in close touch with the workers, and the future can be best taken care of by the proper provision for the training of apprentices. In this training, apart from their ordinary trade, there should be included lectures on economics. How few workmen realize what the secretary of a leading trade union recently pointed out, namely, that 90 per cent of the costs of production is borne, indirectly perhaps but nevertheless borne, by the workers themselves!

The days when an apprentice could be left to his own resources to pick up his trade in the shop have gone. Competition is too keen and it is necessary, in the interests of the men as well as of the manufacturer, that they should be taught on a systematic basis. In the works with which the author is associated in Sheffield there are apprentice classes where the apprentices are given, in the employer's time, lectures by skilled men in the various trades such as fitting, turning and winding, and in addition are given details of the rudiments of rate-fixing and costing, so that they acquire this knowledge in their very early life and are able to consider problems from the broadest point of view. It is hoped that when the apprentices become men they will not have to follow the advice of destructive leaders in trade unions, but will themselves be able to give considered and constructive opinions. The author considers that these lectures, particularly on economic questions, should be extended to the fully-paid workmen, and where they have been given at the Sheffield works he has found that the men take the keenest intelligent interest in the subject.

The author would here like to say a particular word with regard to technically-trained men, i.e. men who take their degrees in engineering. It is essential that our universities and technical schools should include in their curriculum a course of economics. Lectures should also be given on the relation between so-called capital and labour and, further, methods of costing, time-keeping and absorption of overhead expenses should be dealt with. The development of initiative should also have special attention, for when men enter into ordinary industrial or business life, very few have to apply solely technical knowledge. The technical knowledge acquired is very often only a means to an end in so far that it enables one to think on the right lines. Men should be encouraged to take part in open discussion on technical and other subjects, to give them confidence in themselves and to develop their personality. Success depends largely on one's executive acumen, initiative and ability to co-operate.

(*b*) *Works committees.*—The author has found the setting up of a works committee to be the most effective way of establishing confidence between the management and the men. It is a most satisfactory channel for bringing before the workers the management's views on all sorts of questions, particularly managerial and labour problems. Further, it enables the management to obtain the workers' views. This gives the workers the feeling that they are being consulted in matters in which they are directly interested, and this in itself removes suspicion. It must be appreciated that economic production can never be obtained unless the men give loyal support to the management. In this connection the author would say that the value of the works committee's support and assistance in the introduction of the system outlined in the paper, contributed largely to the success of the system. This should be ample evidence of the value of a works committee, for if there is one thing that tends to create suspicion and upset the workmen more than any other, it is a change of management and system.

(*c*) *Foremen's meetings.*—In order to stimulate the foremen's maximum interest in the management of their shops and keep them informed on economic and managerial problems, the author has found that monthly foremen's meetings, at which all problems of general interest met with during the previous month are discussed are of great assistance. The foremen have continually referred to the value of these meetings and to the fact that by this method they have received information on matters which, in the past, have not reached them at all.

(*d*) *Unemployment.*—Generally speaking, it may be gathered from conversation with good workers that the greatest brake on efforts of production is the fear of unemployment, and one cannot help but appreciate this fear; for very often a workman with a wife and family to keep can be thrown out of employment at quite short notice with no immediate appreciable visible means of support. A man working under these conditions is naturally tempted to take all possible steps to delay loss of employment and, if he feels that by exerting extra effort he is only completing more quickly the small amount of work that is available, then one cannot get from him his maximum effort. It is not easy to educate and convince a workman that these actions on his part are quite wrong because they

cause articles to cost more and therefore make it more difficult to obtain further orders. He can think only of the position as it affects him at the moment, not as it may affect him several months later.

It has occurred to the author that, if we wish to get the maximum effort at all times from the workers, this problem must be dealt with in a more materialistic way than by teaching economics. It is suggested that the creation of a special fund dependent on maximum production during times of good trade—this fund to be applied to carry the workmen over periods of depression—would remove this detrimental effect of fear of unemployment. After all, the creation of such a fund for the workers is nothing more than is generally done in the sound financing of an ordinary business, i.e. the setting up of a reserve fund. Why should not the same principle be applied to the worker? Profit-sharing schemes have been suggested and are very sound, but the worker's argument is: "Why should a high-class workman employed by a firm which is on a sound business footing and earns a good profit, receive more than another man, equally skilled and keen on his work, who is working for a firm which does not earn any profit?" And one can appreciate this argument.

In studying this subject the author has come to the conclusion that this sinking fund could very easily be provided in a "payment by results" works in such a way as to be entirely dependent on the workers' efforts, but should be contributed to by both the employee and the employer.

In the engineering industry agreements already exist by which a pieceworker of average ability must be able to earn $33\frac{1}{3}$ per cent bonus. Most workers by extra effort earn considerably more than this. It would therefore be quite feasible to base this "unemployment sinking fund" on this extra effort, by the employer suggesting that for every 1 per cent earned by the worker over the $33\frac{1}{3}$ up to 50 per cent he will give a fixed sum per 1s. to the fund, provided that the employee will also give a fixed sum per 1s.; and further, for every 1s. over 50 per cent bonus the employer would give a further extra contribution in order to promote extra effort. It will be seen that the employer would thus be giving extra payment for extra effort, such money to be applied to insure the worker in times of plenty against times of depression.

The scheme could be applied to the recognized day workers, such as crane men, shop labourers, etc. The same effort could thus be obtained from all employees of the firm to assist the pieceworker in the production of his maximum bonus. The piecework prices would be set to a recognized scale which could be easily seen. If deemed advisable these unemployment funds could also be used for old age and sickness benefits.

It was pointed out to the author by a workman that many men would be suspicious of the scheme because they would think that employers would know how much money the worker had saved in this way, and would use this knowledge to their own advantage in times of depression, or other times. In order to overcome this, the fund might be administered solely by the various works committees or district committees, and thus the employer would have no knowledge of the sums accumulated for any individual. This fund would be available solely for periods of unemployment due to causes other than industrial disputes, it being clearly recognized that an employer could not reasonably be expected to contribute to funds which might at some future period be used for strike purposes. The details of a scheme of this description must necessarily be bound up in a certain amount of trust between employer and employee, and this can be dealt with through the works committee.

The general handling and education of labour having been discussed, the author proposes to deal now with the way in which technical manufacturing information is conveyed to the workers.

Technical Process Department.

This department is obviously necessary in view of the fact that many of the problems connected with the manufacture of electrical machinery cannot be left to the shops to solve. The proper solution very often depends on considerable research work and there are often several ways of getting the same ultimate result, but there is only one way which is the most efficient and cheapest. It is the duty of the Process Department to study these various problems and to issue such instructions as are necessary to everybody concerned to assist them in every way. In addition, records must be kept of these various process specifications so that, should there be a change of supervising labour or operating labour, the new man can look up these specifications and so follow on the lines previously worked to. An example of this occurred some years ago, when a man who had been shrinking slip-rings on to mica-covered bushes suddenly left and another man was put on to do the job. The foreman gave what he thought were the correct instructions to carry out the work. About two months afterwards, however, when these slip-rings began to reach the assembly department, it was found that they were loose. On investigation it was discovered that there was no specification and therefore no record of what allowances the man, who had been doing the job for many years, used. In consequence of this a number of experiments had to be carried out and a specification prepared. It must also be remembered that the workman or shop foreman is not always familiar with the details that the designer has in mind. It is therefore of the utmost importance that process specifications should be prepared, particularly drawing attention to the points that the designer wants. In a case which recently came to the author's notice ventilated field coils were provided in a certain machine but no reference was made on the drawing to the fact that the top and bottom washers on the coils should be provided with an opening to allow the air to pass through. In consequence it was not until the machine was assembled and tested that the fact of these ventilating ducts being closed up was discovered.

This department also issues the necessary specifications to enable the buyer to purchase the right sort of materials, many of which have to fulfil highly important functions of which the manufacturer has

little knowledge. This section works very closely in conjunction with the research departments.

Appendix 1 gives an example of a manufacturing process, and Appendix 2 shows a purchasing specification for asbestos millboard, showing how the requirements to meet special technical conditions are taken care of.

Having dealt with the handling of labour and the transmission of technical information to the shops, let us now consider the instructions with regard to a mechanical operation.

TABLE 2.

M.P. & R.F. Dept. Dept. "D." Piecework Time based on one off. Section I.

Apparatus: . Process Sheet No. 723. Order No.: E.100.

Drawing No.: Item No. 1. Style: . Date: 3/4/1922.

Seq. No.	Operation	Finish*	M/C No.	M/C Rate	Group No.	Labour Rate	Class of Labour	Process Time	Process Price	Awards	F.E.	Total	No. off	Tool No.
				s. d.		s. d.		h. m.	s. d.	s. d.	s. d.	s. d.		
1	Plane joints and feet	D	M 3	3 4	68	45 0	Man	13 0	16 3	3 0	43 4	62 7	1	
2	Mark joints for drilling		H	1 9	11	49 0	Man	1 0	1 6	0 3	1 9	3 6	1	
3	Drill and S.F. joints	D	M 31	2 6	24	30 0	Man	4 0	5 2	0 11	10 0	16 1	1	
4	Joint up		H	1 9	11	24 0	Youth	1 0	0 8	0 2	1 9	2 7	1	
5	Mark setting line for boring ..	D	H	1 9	11	49 0	Man	1 0	1 6	0 3	1 0	3 6	1	
6	Bore and face		M 6	3 4	62	49 0	Man	10 0	14 0	2 3	33 4	49 7	1	
7	Mark for drilling complete.. ..		H	1 9	11	49 0	Man	3 15	4 7	0 9	5 8	11 0	1	
8	Drill and S.F. for poles and feet. Drill and tap for eye-bolts	D	M 22	3 4	63	39 0	Man	8 45	9 10	2 0	29 2	41 0	1	
9	Drill and tap for rocker	D	M 31	2 6	24	39 0	Man	2 15	2 7	0 6	5 7½	8 8½	1	
10	Fettle		H	1 9	11	35 0	Semi-skilled	15 0	15 0	3 5	26 3	44 8	1	
						Total ..	..	.. ..	71 1	13 6	158 7½	243 2½	1	

* A = ground finish. B = lap finish. C = water finish. D = dry finish. E = semi-finish. F = rough finish.

RATE-FIXING AND MECHANICAL PROCESS DEPARTMENT.

In establishing a department of this description, the selection of the personnel is a matter that requires careful attention. In many engineering works it will be found that the piecework times are fixed by the foremen or by rate-fixers who have graduated from the ranks of the workmen without any special training apart from that obtained in the workshops. If the product is of comparatively simple design and construction such an arrangement is generally adequate, but for the complex nature and variety of the parts that go to make up an electrical machine, and owing to the keenly cut prices which have to be quoted to enable home manufacturers to compete with the foreigner, it is essential that not only the piecework time, but the machine and type of tool to be used and the class of finish to be achieved for every operation, be decided by engineers who have the necessary workshop experience and, in addition, who thoroughly understand the functions of the multifarious component parts to be handled.

In order to take advantage of the full capacities of the machine tools and of the improved methods which are frequently introduced by the mechanical process engineers in collaboration with the tool drawing office, it is desirable that the Process Department should consist of two distinct branches. One branch should deal almost entirely with time studies of the feeds and speeds which can be obtained with the improved methods and appliances, and should thereby supply data to the other branch consisting of the process engineers. In this way we can ensure that all piecework times are arrived at on a definite basis with respect to feeds, speeds, etc., and we can consequently eliminate the startling discrepancies which are often found to obtain under those rate-fixing systems where the individual is allowed to express his own opinion.

The Process Department compiles a process sheet for every item for which a drawing is made, and on each process sheet will be found the following information in addition to the operations :—

(1) Process sheet number.
(2) Drawing number.
(3) Item number.
(4) Description of item and style of machine for which it is required.
(5) Minimum number of items to be manufactured at a time to permit of processed time per item being adhered to.
(6) Machine tool to be used if a machining operation.
(7) Hourly rate of the machine tool.
(8) Class of labour to be used on each operation.
(9) Rate of labour to be used on each operation.
(10) War allowances.
(11) Factory expense.
(12) Total cost of labour and factory expense.
(13) Sequence in which the operations are to be performed.
(14) Shops in which the operations are to be performed, and to which consequently the process sheets are to be issued.
(15) Class of finish.

Table 2 shows a typical process sheet for the yoke of a rotary converter.

To ensure that the process sheets are supplied to the departments concerned, the process sheet number and the departments to which the process sheets are to be issued are given against the various items on the

manufacturing specifications which are prepared by the drawing office and distributed by the Production Department.

In fixing a piecework time the process engineer bases his calculations on the following assumptions :—

(*a*) That the material will be of average quality of its kind.
(*b*) That the machining allowances will be normal.
(*c*) That the man who is to handle the job will be of average skill, so that he should have no difficulty in making time and a third on the job.
(*d*) That the best machine (if a machining operation) will be available at the time the job goes through.

If the time allotted to the job is disputed by the operator, he refers the matter to his foreman, and if the latter also disagrees with the piecework time, the time-study man for that department is called in to demonstrate what is actually possible. The operator also has the right to scrutinize the detailed figures as calculated by the process engineer which go to make up the total time allowed for the operation (this information, by the way, is filed away in the Process Department with every process sheet) so that he can, if he wishes, point out in what respect he considers the piecework time to be at fault. If it is found that the time allowed is incorrect through some extraneous circumstance, such as unusually hard material involving lower feeds and speeds, defective material, or excessive material allowances on machined surfaces, or owing to the best machine for the operation not being available, then an additional piecework time fixed by the time-study man is allowed for the job, covering the excess time involved only. Under such circumstances the processed time would not be altered.

Whatever the cause, the matter is brought to the notice of the Process Department and, in the case of faulty material, is taken up by them with the suppliers of the material with a view to obtaining a rebate for the extra cost involved in machining this material or, at any rate, ensuring that further supplies will tend to be free from such faults. If, however, the time student's investigation proves the processed time to be incorrect without any such extenuating circumstances, the process sheet is immediately altered by the process engineer and the data from which the processed time has been derived is corrected accordingly. In dealing with disputes, absolute frankness is necessary, and if there is any doubt about the accuracy of the processed figure, particularly of that factor which cannot easily be calculated and is more a matter of experience, namely, the setting up and handling times, then the matter should be carefully investigated and the operators given the benefit of any doubt, unless it is ultimately settled incontestably by demonstration that the processed figure is correct.

Immediately a new drawing is completed by the drawing office, a copy is sent to the Process Department and the process sheets are issued as quickly as possible so that the piecework time is fixed well in advance of the operation being performed. This is very important, as nothing annoys the operators more than not knowing the price they are to be allowed for a job until after it has been commenced or completed, and under such circumstances an atmosphere of suspicion is engendered between workmen and management that is very difficult to combat.

In addition to establishing all piecework times on a systematic basis, the further advantages accruing from the system are as follows :—

(1) The Process Department is in a position to keep the Purchasing Department posted as to the relative merits of materials supplied by different manufacturers. For instance, in connection with steel castings it was found that one firm quoted a substantially lower price per ton for castings than a competitive firm. Orders were placed with both firms and it was ultimately proved that the castings from the latter firm were much cheaper in the long run, as the material was better to machine, the castings were sounder and more accurately moulded and the percentage of rejected castings was much lower.

(2) The Process Department can readily supply the Estimating Department with accurate data for the preparation of estimates, and also advise when reductions can be made owing to the introduction of improved methods or machinery.

(3) Owing to the piecework time being based on the best machine tool being available, certain machines are called upon to such an extent that some of the work necessarily has to be performed on less efficient machines. Records are kept of the extra cost of the work on these machines, and the losses thus incurred will show whether the inefficient machines are worth retaining in service.

(4) A copy of all process sheets is sent to the works costing section so that actual costs can be compared with processed costs as the parts are manufactured.

(5) Disputes regarding piecework times as processed have frequently brought to light the fact that the methods of production as carried out before the introduction of the system were entirely wrong and entailed considerable unnecessary expense, also in numerous cases super-accuracy of finish was being put into parts that were unimportant.

(6) The process sheets enable the Production Department to deduce exactly the time required to manufacture any piece of apparatus. Table 3 shows information taken from the process sheet and assembled to show how the total machine-hours and man-hours on each particular class of machine would be ascertained.

(7) The process engineers frequently find when processing a part that reductions can be made in the cost of production by an alteration in the design which will not interfere in any way with the functions of that particular part.

The production machine basis sheet is prepared from the process sheets. This will be dealt with under the heading of "Production Department."

The author believes that the system has been dealt with in sufficient detail to illustrate the broad principle on which the Rate-Fixing Department should be organized.

The handling of labour, and the transmission of technical and mechanical operation information to the

TABLE 3.

Part of Progress and Production Chart, in Machine-Days and Man-Days.

Machine: Type X.

Part	No. Off	Material	Plane	Mill	M.O.	Drill	Slot	Turn	Fit	Ass.	Fettle	P'ch'gs	Build	Make Coils	Imp. & Wind	Bal'ce.	Erect	Fin.	Paint	Test	Saw	Detail	Total Man-days
Yoke	1·0	Cast steel	1·5	—	0·5	2·5	—	1·25	—	—	0·75	—	—	—	—	—	—	—	2·0	—	—	—	8·5
Poles (laminated)	6	Core steel	—	—	0·1	0·25	—	—	—	—	—	1·5	1·0	—	—	—	—	—	—	—	—	0·25	3·1
Rivets, washers and liners ..	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2·0	2·0
Dampers	—	Copper	—	—	0·1	1·5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0·5	4·0	6·1
Interpoles..	6	Steel plate	—	0·5	—	0·5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0·5	—	1·5
Studs and screws	—	—	—	—	—	—	—	1·25	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1·25
Shunt coils	6	Copper	—	—	—	—	—	—	—	—	—	—	—	5·5	—	—	—	—	—	—	—	—	5·5
Series coils..	6	Copper	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Interpole coils	6	Copper	—	—	—	—	—	—	—	—	—	—	—	7·5	—	—	—	—	—	—	—	—	7·5
Connections	—	Copper	—	—	—	—	—	—	—	—	—	—	—	4·5	—	—	—	—	—	—	—	—	4·5
Field assembly	—	—	—	—	—	—	—	—	—	2·75	—	—	—	—	—	—	—	—	0·5	—	—	—	3·25
Total machine-days for each class of machine ..			1·5	0·5	0·7	4·75	—	2·5	—	2·75	0·75	1·5	1·0	17·5	—	—	—	—	2·5	—	1·0	6·25	43·2

TABLE 4.

Part of Main Production Chart.—Output Programme for September.

Customer	Machine	Frame size	Estimated weight in tons	Delivery promise to customers	Sheffield delivery promise	Principal specification sheets required	Principal material to be in	Operations: Machining	Operations: Core building	Operations: Winding	Operations: Assembling	Operations: Test, paint and pack	Remarks
A	Type M.2 motor	*a*	4·55	30/7/21	30/7/21	11/3/21	8/5/21	13/6/21	17/6/21	4/7/21	9/7/21	30/7/21	Delay due: late receipt of material. Machines overdue.
A	Type M.2 motor	*a*	4·55	30/7/21	30/7/21	11/3/21	8/5/21	13/6/21	17/6/21	4/7/21	9/7/21	30/7/21	
A	Type M.2 Motor	*a*	4·55	30/7/21	30/7/21	11/3/21	8/5/21	13/6/21	17/6/21	4/7/21	9/7/21	30/7/21	
B	Type G.2 generator	*b*	8·3	31/7/21	31/7/21	28/3/21	25/4/21	3/6/21	8/6/21	1/7/21	7/7/21	30/7/21	Delay due: difficulty in works. Machine overdue.
C	Type G.3 generator	*c*	7·4	8/8/21	6/8/21	15/2/21	12/4/21	24/5/21	28/5/21	21/6/21	27/6/21	20/7/21	
D	Type R.2/3 rotary	*d*	7·6	31/8/21	31/8/21	9/5/21	1/6/21	8/7/21	13/7/21	30/7/21	6/8/21	27/8/21	
E	Type R.9/11 rotary	*e*	11·0	6/9/21	6/9/21	4/3/21	31/4/21	22/5/21	27/5/21	22/6/21	30/6/21	22/7/21	
F	Type R.7 rotary	*f*	7·5	10/9/21	10/9/21	19/3/21	7/5/21	25/6/21	29/6/21	25/7/21	29/7/21	20/8/21	
G	Type T.A.15 turbo-alternator	*g*	10·4	10/9/21	10/9/21	29/2/21	24/4/21	13/6/21	29/6/21	3/8/21	10/8/21	30/8/21	
H	Type R.10/11 rotary	*h*	28·0	11/9/21	11/9/21	27/5/21	24/6/21	22/7/21	28/7/21	25/8/21	1/9/21	8/9/21	
H	Type R.10/11 rotary	*h*		11/9/21	11/9/21	27/5/21	24/6/21	22/7/21	28/7/21	25/8/21	1/9/21	8/9/21	
H	Type A.C. starting motor ..	*j*		11/9/21	11/9/21	29/5/21	10/6/21	22/7/21	26/6/21	16/8/21	20/8/21	8/9/21	

men have been dealt with. The obtaining of material and its passage through the shops will now be discussed.

Production Department.

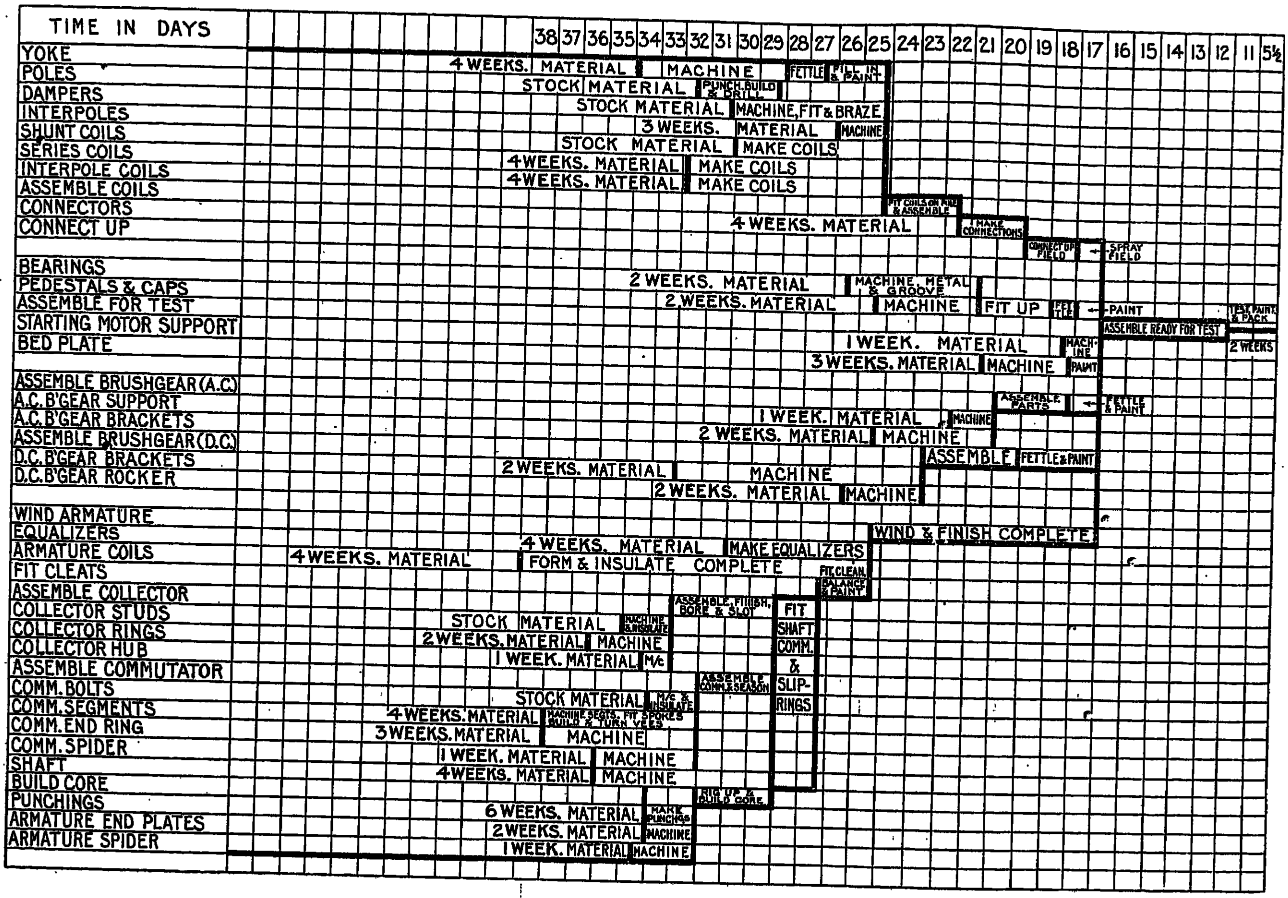
In describing the organization of this section the author would add a few words of warning in choosing the man to run this department. Beware of the high qualification claimed by applicants for the position—such as efficiency engineer and production expert—who are frequently experts in theory and not in practice.

The works manager, who it is assumed is a man of education and very wide practical experience, should direct and control the operation of the Production Department through the chief of that department, in order to ensure that it is not systematized beyond practical and commercial limits. This is very important, as a number of companies have undoubtedly experienced serious financial difficulties through the operation of production theorists.

The capacity of the shop is fixed by the works management in conjunction with the requirements laid down by the sales organization and the capacity fixed by the Production Department. The main shop programme is then prepared. Table 4 gives an example of a portion of a monthly sheet, part of a main production chart, for a shop the normal month's capacity of which was considered to be 300 tons. Each month is laid out similarly and the Commercial Department is advised by the Production Department of forward requirements in good time to keep the shop fully employed. If the orders received monthly exceed the shop capacity, the fact is revealed in good time to enable steps to be taken to deal with it by extending the works, obtaining outside help or increasing the working hours or delivery periods. A list, revised monthly, is sent to the Commercial Department showing the delivery times to be quoted in tenders for all types of machines.

Table 5.

Machine Production Chart.—Summary for Type X Machine.



When an order is received it is placed in its proper position in the main programme, which is based on the chart shown in Table 5. The dates are then fixed when the manufacturing information and materials must be available to enable the promise to customers to be kept. These detail requirements are recorded systematically so that they are automatically urged. This urging is divided into three sections:—

(1) Manufacturing information, including specifications and drawings.

(2) Material.

(3) Work in different departments of the shop.

The urging is run on a daily basis so that everything is urged at the right time. This can be easily arranged by having a card for each manufacturing day under each sub-section and entering on it all requirements due on that day to fulfil the manufacturing programme. A fixed period before the requirements are due (if they have not been received) they are specially urged.

For the sake of convenience the Production Department is organized in two sections, one section handling specification sheets, the main production programme, obtaining materials from outside suppliers through the Purchasing Department, and all work inside the office, and the other dealing with materials after receipt in the shops, and the production generally in the shop. The closest co-operation is essential between these two sections.

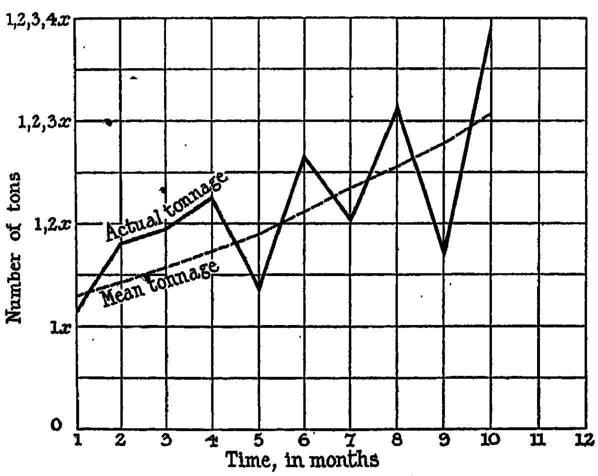


FIG. 2.—Tonnage output.

All manufacturing information from the drawing office is passed through the Production Department and all drawings are subsequently passed through the tool drawing office so that all jig and tool designs are prepared to the date fixed for completion to ensure tools being available by the time material is received.

From the main production chart, records (again on a date principle) are prepared for the foremen of each department in the shop.

Table 6 gives an example of a foreman's weekly production list, as supplied to him by the Production Department. Only one week's work is reproduced in this table but, in practice, instructions for four weeks are given. The shop clerk, who will be at the foreman's desk, will handle these and will be under the general control of the chief production engineer as far as the production matters are concerned. It is the duty of these shop clerks to keep the foremen advised where the material is after receipt from suppliers and to get out the necessary drawings and tools to enable the work to be proceeded with at the right time.

TABLE 6.

Large Machine Department.

Week commencing March 7, 1921. The following machining to be finished by the dates specified.

Name: Mr. X.

Job No.	Date	Customer	Description	Remarks
275/3681	8/3/21	A	625/815 kW rotary	Material received 18/2/21
3685	9/3/21	B	500-h.p. induction motor	Material received 19/2/21
E.139	12/3/21	C	380-h.p. motor	Material received 16/2/21
E.152	10/3/21	D	110-h.p. induction motor	Material promised 24/2/21
E.163	8/3/21	E	100-h.p. induction motor	Material received 10/2/21

Production meetings are held weekly at which the shop superintendent, buyer, production chief and foreman are present, when details of progress, etc., are discussed.

The curves in Fig. 2 show the effect of a production department's work from its inception until reaching the legislated tonnage output.

The Production Department is responsible for fixing the maximum and minimum stock quantities for all materials stocked in stores.

A return is made to the works manager each week from each department of the items which have not been completed according to schedule, and the reasons for such non-completion.

For a certain works of 700 hands the production staff consisted of:—

1 chief;
2 assistants;
3 clerks; and
1 typist,

exclusive of foremen's clerks, of whom there were 4.

Having dealt with labour and the necessary instructions to labour for technical and mechanical operations to be used in conjunction with the material provided, let us now consider the question of inspection of this material in its initial stages and during its progress through the shops.

INSPECTION DEPARTMENT.

In order to ensure that a piece of electrical apparatus when it reaches the test bed has the very best chance of turning out satisfactorily, both to the customer and to the reputation of the manufacturer, it has been found of the greatest advantage to arrange for the inspection and testing of details as the manufacture proceeds through the works. This is of great importance, because if a machine can be shipped immediately after test, and if expensive repairs can be avoided,

a manufacturer is better able to fulfil the obligation of delivery.

In the first place, arrangements must be made to inspect and test the raw materials, for, as mentioned above, with electrical machinery the range of materials is so wide that it provides many channels of possible failure. The standard for these materials is taken from the purchasing specification prepared by the Process Department.

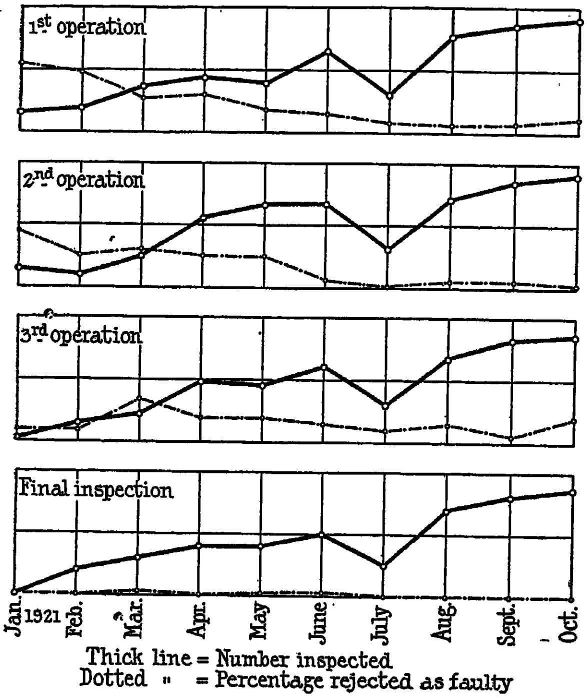


FIG. 3.—Inspection of gear wheels and pinions.

The author has found it necessary that the Inspection Department should take entire responsibility for the testing and inspection of raw materials, but in the shops he prefers that representatives of the Inspection Department should be looked upon in a similar light to customers' inspecting engineers. In other words, they are a safeguard to the management and the foremen, but it is very important to leave to the foremen the real responsibility for the quality of the product. It is necessary that the foremen should feel that the Inspection Department is established to assist them in avoiding mistakes. On no account should the impression be gained that they are spies on the manufacturing section. It is therefore essential that the inspectors should co-operate with the manufacturing section to improve the product and avoid mistakes, rather than criticize. This latter course should be taken only where gross negligence or wilful opposition occurs. The number of inspectors depends on the class of work that has to be dealt with, and as a rough guide the author has found the following proportions to be satisfactory:—

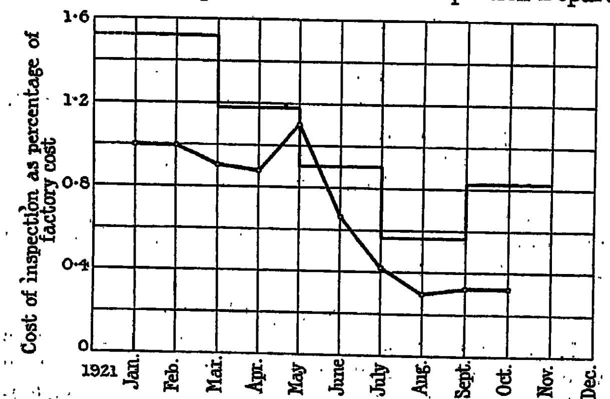


FIG. 4.

Large machine section requires 1 inspector to 60 hands.
Small machine section requires 1 inspector to 70 hands.
Large assembly section requires 1 inspector to 45 hands.
Small assembly section requires 1 inspector to 35 hands.
Large winding section requires 1 inspector to 40 hands.
Coil and insulation section requires 1 inspector to 40 hands.

(NOTE.—Cost of the above is approximately 0·7 per cent of factory cost of output.)

Figs. 3 and 4 give some indication of the results obtained by the introduction of an inspection system. The former shows the small number of defects that appear in the final completed article, and the latter the fall in the number of defects in the final testing department after the introduction of a detailed inspection system. A curve of comparative costs is also shown.

COSTING DEPARTMENT.

To manufacture a varied product satisfactorily it is necessary to have proper records to guide all parties as to the cost of the product in direct labour and materials and also overhead expenses. During the introduction of a costing system, the first essential to impress on the members both of the manufacturing and of the costing staff is that the closest co-operation must exist between them. The Costing Department is not a spy on the Manufacturing Department, but a useful and constructive portion of the manufacturing organization. Its duty is to assist the manufacturing section by giving such figures and help as to enable them to ensure that excess costs do not occur. It must be realized that the foreman in the shop cannot possibly carry the cost of all different operations and factory expenses in his head, and he must be encouraged to co-operate with the Cost Department and to have confidence that they will assist him.

Costing can be conveniently divided into two sections:—

(1) Consisting of direct labour and materials.
(2) Consisting of factory overhead expenses.

(1) *Costing direct labour and materials.*—The author has experienced great difficulty in cases where costs are not available until a machine is finally completed. By this arrangement, if a machine takes several months to manufacture it is impossible to investigate operation costs because they are received a considerable time after the operation has been carried out. This emphasizes the necessity of a costing system being elastic as well as prompt.

An elastic system has many advantages, and one with which the author is now acquainted has been found to contain the very elements necessary to avoid losses which might recur in possibly the course of two months in a works where repetition work is engaged in to some extent. It also provides the means of producing efficiently and cheaply, by reason of the fact that particulars can be obtained of the time taken, the number of operations employed, the size and rate of machines used, and the cost of labour.

For many reasons it is of the utmost importance that a sound costing system be installed. In this connection, in the particular works with which the author is associated, the features that have had most consideration and which are of paramount importance are: To provide operation costs as quickly as possible after an operation has been carried out, so that the actual cost can be compared with the planned process. After all operations on a piece of apparatus have been thoroughly standardized and the comparison between cost and estimate shown, and the planned piecework prices fixed, then, provided a proper check is kept on daywork, there is not the same need for keeping a comparison of operation costs, and the final cost of the completed machine is the only check that is essential. In the starting up of manufacture of a piece of apparatus of new design, however, operation costs, prepared immediately after the work is carried out, are essential.

In order to make this scheme operative, a complete detailed list of the planned operations should be forwarded by the Mechanical Process Department to the Cost Department, each operation to be given a number for the purpose of comparison.

In many works what is known as the "Hollerith" card index system has been introduced for the recording of costs. This is certainly very sound, but in its introduction very careful consideration must be given to the question of flexibility, for unless the system is properly laid out the Hollerith system can be far from flexible. The most important point about a costing system is that it must not give either too little or too much. If the former, it becomes useless because the information is incomplete, and if the latter, more money is being spent than the value obtained from it. It is obvious, however, that it is better to have too much than too little.

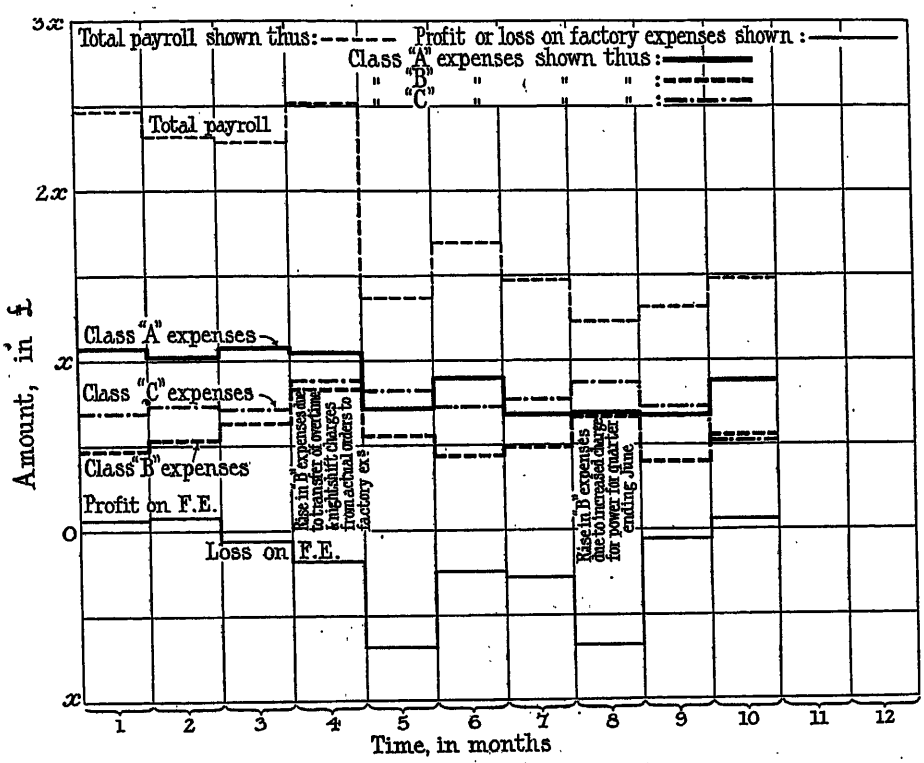


FIG. 5.—Relationship of pay-roll to expenses.

(2) *Costing factory overhead expenses.*—The overhead charges must be properly provided for and, in the author's opinion, a machine rate basis is the only sound way to effect this. A percentage on labour is quite wrong and to emphasize this one has only to take the case of a man and a boy working on the same machine. The man's rate may be 1s. 6d. per hour, and by the percentage basis the overhead charge on his labour, if the ratio is 100 per cent, would be 1s. 6d. For a boy on the same tool at 6d. an hour the charge would be 6d., and, if one considers in detail all the expenses that go into overhead charges, it will be found that the charges per hour for a lower rate of labour are quite as much as for the higher, and very often more, as boys damage more tools and require more supervision per unit of output. With the majority of the

machine tools at the author's works the machine rate basis is taken as 40 hours per week, the difference between 40 and 47 being the average loss of time in the running of the machine due to various causes, such as breakdowns, men absent, getting together tools, etc. The machine rate basis is arrived at by allocating a portion of the fixed charges (such as rates, rents, taxes, depreciation, etc.) for the floor space occupied by the machine and the surrounding space necessary for storing the raw and finished product.

Power charges are obtained by taking the actual power measurement of the machine. Tool charges are arrived at by estimating the value of tools used in a definite period and employing this as the basis for an average hourly cost for tools. Hourly charges per machine are arrived at for depreciation, general shop labour and materials, operation of cranes, etc.

The author has heard the opinion expressed that it would be difficult to apply this system to an old works. However, at the works with which he is associated in Sheffield, employing up to 1 000 hands, this system was instituted and was running satisfactorily in 3 months.

Having arrived at this basis of machine charge, it is important to see that the factory expenses are collected and recorded in such a way that they can be easily watched to make sure that there is no mistake in the estimating of overhead charges, and that proper figures have been fixed for absorption. The assembly of these expenses should be such that they can be easily understood and watched by the heads of the various departments. In the works referred to above, these expenses are recorded in the following three groups, each item being given a number, to which all expenses on that item are charged :—

(A) Items controlled by the foremen. Full particulars of these are sent to each foreman monthly, so that he can take an intelligent interest in the money he is actually spending and keep down unnecessary expenditure.

(B) Items controlled direct by the Superintendent of the works.

(C) Expenditure controlled by the Board and General Management.

Lantern slides will be exhibited showing details of these groups.

This type of division may not be necessary in a smaller works, but the basis should be the same, for this paper was written to draw attention to a basis of an organization, as before mentioned, rather than to give details of a particular scheme which may not be applicable to more than one works.

By this method of recording factory expenses a more direct interest in the efficiency of the department is created, because the foreman realizes that he has something which he is able to control.

Fig. 5 shows the variation of labour and factory expenses and their relation to the absorption of factory expenses. In many works it is the practice not to give foremen details of this description. The author considers that a foreman should be looked upon as the manager of his own department and should be given such information as will enable him to manage. The owner of a factory would not attempt to manage it unless he had the necessary figures put before him.

Finally, a monthly summary of expenses is prepared, as shown on the lantern slide.

Relation between Output and Costs of Production.

The question of factory expenses has already been referred to. The author will now endeavour to show the distribution of these expenses. For the sake of simplicity let us consider a factory that is making one class of machine of one size. The factory cost of this machine consists of the cost of material, the cost of labour and its share of the factory expenses, and this share of the factory expenses is proportional to the output. In other words, the total factory expenses divided by the number of machines shipped per year equals the factory expenses chargeable to each machine. For example, let us assume that the normal output of a certain workshop under a moderate management is 1 000 machines a year. The basis on which the selling price is arrived at is obtained as follows :—

	£
Cost of material	20 000
Cost of labour	6 000
Factory expenses	6 000
Estimated selling expenses	8 000
Total cost of 1 000 machines ..	40 000
Total selling price (including 10 per cent profit)	44 000
Selling price per machine (including 10 per cent profit)	£44

Now let us consider this same shop working under bad management and producing only 500 machines per year, and the same shop under a very efficient management, working day and night, producing 2 000 machines per year. The table below illustrates very clearly the effect of this on the possible selling price. It will be noted that we get the enormous difference in price of 50 per cent for the same article.

Output per Year.

	Under bad management. 500 machines	Under excellent management. 2 000 machines, working day and night
	£	£
Cost of material	10 000	40 000
Cost of labour	3 000	12 000
Extra for night work ..	—	3 000
Factory expenses	6 000	6 000
Extra for night work ..	—	1 500
Selling expenses	8 000	9 000
Total cost of machines ..	27 000	71 500
Total selling price (including 10 per cent profit)	29 700	78 650
Selling price per machine (including 10 per cent profit)	£59·4	£39·325

These two figures compare with £44 for the factory manufacturing 1 000 machines a year. They are com-

parative for a high-class electrical engineering shop, where the overhead charges are relatively high due to the necessity of employing a large staff in the engineering and draughting offices and in the selling section.

This subject can also be studied from another point of view, namely, that of profit. If we assume that the motors have been sold under all conditions at the fixed price of £44, the effect of decreased output is shown clearly in the following table:—

Output per Year.

	1 000 machines	500 machines	2 000 machines (working day and night)
	£	£	£
Cost of material	20 000	10 000	40 000
Cost of labour	6 000	3 000	12 000
Extra for night work ..	—	—	3 000
Factory expenses ..	6 000	6 000	6 000
Extra for night work ..	—	—	1 500
Selling expenses	8 000	8 000	9 000
Total cost of machines ..	40 000	27 000	71 500
Total sum received (at £44 each)	44 000	22 000	88 000
Loss on working	—	5 000	—
Profit	4 000	—	16 500

From this it will be seen that a loss of £5 000 is turned into a profit of £16 500, merely by increasing the output. This clearly shows the importance of the selling staff obtaining orders, and the works staff doing everything possible to enable a greater output to be obtained than that estimated for.

In conclusion, the author would like to urge that the principles outlined in this paper can be applied very profitably outside the ordinary manufacturing problems. For instance, the power station engineer increasing his plant can lay out his extension programme to ensure that his orders are placed at the right time, i.e. neither too early nor too late, and thus avoid:—

(1) Capital lying idle and plant being delivered before it is required.
(2) Delays in completion (involving capital lying idle on account of plant that is delivered in time waiting for plant that is late).

Further, this will avoid plant being stored in the works after the foremen and men have been urged to complete it. This, it will be appreciated, has a very bad moral effect on all those concerned.

It will be of interest to know that the author has recently returned from a tour of inspection of conditions in American works, where he did not find any organization which could improve that outlined in this paper for handling a varied product. Further, he found that the average manual employee in the United States gives a greater output than is generally found here. In the author's opinion this is accounted for by the confidence established there between employer and employed. The necessity for the establishment of such confidence in this country and the suitable methods for realizing it are emphasized throughout the paper.

We, as electrical engineers, can certainly take great pride in the fact that our efforts have already been of very considerable benefit to the community, particularly to the working classes, as, for instance, they are now able to go to their work by tram at very cheap rates and in a very short time, whereas previously they often had to walk miles. I think all of us realize that our work has only begun and that by proper organization in the manufacture of electrical apparatus of every description we should lead to the more extended use of electricity for heating and power.

A number of lantern slides will be exhibited showing a shop laid out with galleries supplying main centre aisles, and a shop laid out to give continuous advancing operations on one floor.

In conclusion, the author must express his thanks to Messrs. The Metropolitan-Vickers Electrical Co. for giving permission to publish so much information on the running of their Sheffield works. He is also indebted to Mr. H. F. Brown and Mr. McMurray for assistance in editing proofs during his absence in America.

APPENDIX 1.

Process Specification for Moulding Mica to End Rings for Large Rotors.

Material.—Mica splittings, Grade 4 (area 2 to 4 square inches), shellac varnish (specific gravity 0·930).

Process.—The moulding mica shall be cut in sections and the part of the mica which is to fit over the tapered end of the ring shall have fingers cut to the depth of the spigot.

The ring shall be thoroughly cleaned with a cloth which has been dipped in methylated spirits, and then wiped dry. A coat of shellac varnish (specific gravity 0·930) is then applied to the ring where the first section is to be placed. The moulding mica is then placed on a hot-plate and one side is given a coat of shellac varnish (specific gravity 0·930). As soon as the section is soft enough for moulding it is placed in position on the ring and rubbed down with a dry cloth. The end with the fingers cut in is to be ironed down with an iron. All the following segments are then treated in exactly the same manner, but when placed in the ring the butt joint is made leaving about 1/16-inch clearance between the segments. All the following segments are then placed in the ring in the same manner.

Four layers of 1/32-inch moulding mica (mica is milled 28 to 32 mils) are to be built in the ring in the same manner as the first layer, staggering the joints as each layer is built.

It is essential that the thickness of mica shall be the same in each layer.

Moulding.—The mould is heated in a gas flame at a temperature of approximately 210° C., and then placed in the mould and screwed down tight. At the same time a cold mould shall be placed on either side

of the hot mould, to prevent getting any creases in the mica where the edge of the hot mould is pressing.

This operation is repeated until the whole of the ring has been moulded, and care should be taken that the mould is not unscrewed until it has cooled down to a temperature between 30–40° C.

When the above operations are completed a large mould made to fit inside the ring is placed in position and screwed down hand-tight by means of clamps. The whole is then placed in an oven, the temperature raised to 150° C., and baked for 15 hours. As soon as the temperature has reached approximately 90° C., the ring is removed and screwed down as far as possible. It is then returned to the oven to complete the baking process.

After removal from the oven the ring is allowed to cool down to a temperature of 30–40° C., before removing the mould.

APPENDIX 2.

Purchasing Specification for Asbestos Millboard.

General.—This specification covers a soft, porous, rough-surfaced asbestos millboard suitable for use in the manufacture of arc shields, etc.

Dimensions. Thickness.—The asbestos millboard will be ordered of a nominal thickness of 0·063 inch with tolerances ± 0·01 inch.

Size of sheets.—Sheets will be supplied in sizes from 3 to 4 feet square.

Finish. Stiffness.—The sheets shall be sufficiently stiff to permit of their being readily handled for the purpose of cutting and sawing to any required shape.

Surface.—The material shall present a rough porous surface which will readily permit the penetration of silicate of soda during process of manufacture into arc shields.

Physical properties. Softening.—When placed in a hot solution of commercial silicate of soda (specific gravity 1·25 at 20° C.) and maintained at this temperature for 1 hour, the sheets must become soft and pliable and must not become pulpy or fall to pieces when handled.

Moulding.—Ten pieces of asbestos millboard 5 inches × 5 inches will be soaked for 1 hour in silicate of soda (specific gravity 1·25 at 20° C.) maintained at 85 to 90° C., after which they will be placed between metal plates and subjected to a pressure of 300 lb. per square inch and to a temperature of 100° C. for 3 hours. This test should produce a hard, solid piece which when struck with a piece of metal produces the ring of a tile or hard brick.

Discussion before The Institution, 18 January, 1923.

Mr. H. Mensforth: I think that in dealing with workpeople the author adopts rather too patronizing an attitude, and particularly is this the case in connection with the teaching of economics. He mentions the latter on so many occasions that one is almost driven to the conclusion that he thinks that it will act as a sort of anæsthetic on the workman, and that the workman accepts the employer as a proper teacher of economics. I do not think that such is the author's opinion, though that is a possible construction to put on his paper. My experience is that when one talks economics with a workman one finds that he is not so ignorant on the subject as one might suppose. He has his own views, and one would not get very far in teaching him this subject as usually understood by employers. For instance, one of the first questions that a workman would put would be as follows: "Separating the factory cost (which consists of labour, factory overhead, and material) from the selling price, what is the selling price? One will often find that the factory cost which includes the above components is only 50 per cent of the selling price, and if this is so, cannot savings be effected in this direction?" A further point is that in dealing with factory expense labour itself, in some form or other, is one of the largest components, but labour (i.e. productive labour) is not the largest component of the factory cost of a piece of material, and the tendency to-day is to devote too much attention to this element of the cost of the product. I notice in regard to the organization charts which the author gives that he excludes what I should consider to be one of the most important sections. I refer to the estimating section. The author mentions a sinking fund to be derived from a piecework effort of the workmen. Whilst the principle may be sound, and whilst the author's views thereon are undoubtedly so, I think that the method adopted of expressing it is rather unfortunate, because it is stated that the fund is solely dependent upon the workmen's efforts. The author makes a statement about a 33⅓ per cent bonus, and this should, I think, be corrected. The fact is that the agreement between the employer and the employee provides that a man of average ability shall be able to—not must—earn a bonus of 33⅓ per cent upon his basic rate, not upon his wages. As regards piecework price-setting, I think that the author has forgotten one fundamental thing to which attention should be drawn, namely, that the agreement which exists between the employer and the employee is that the price paid shall be an agreed price, and that all piecework prices shall be subject to such agreement and also to mutual negotiations. The author points out what machinery will operate provided the man is dissatisfied, but he does not point out what the machinery or organization is which will operate if the disagreement continues after the stage to which he refers. The function of the table on page 350 is to exhibit the influence of output upon cost. I wish that the problem were as simple as is indicated therein. There are many additional factors to be considered. In the first place, the author gives a factory expense component of £6 000. There is no engineering concern, of which I have any knowledge, working with a factory expense component of £6 000 associated with

a labour component of £20 000. Further, I do not know of any concern which can increase its output by 100 per cent, i.e. from 1 000 to 2 000 units per year, without a material increase in its overhead charges. The cost of maintenance of the machinery is very much higher; the cost of power also is very much higher. Extra lighting and heating are necessary, so that the figure might be quite different. I admit at once that some advantage would accrue, but it would not be as great as the paper seems to indicate. As regards works committees, I am in full agreement with the author. I entirely sympathize with the idea of putting before workmen any fact which they can absorb, taking steps which will help them to absorb it and doing anything within reason which will make their job more interesting. The majority of works committees in this country have failed because the employers have not had sufficient courage to give the men scope to be operative. They have been hedged round by constitutions. The only efficient constitution for a works committee, according to my experience, provides that the committee is definitely concerned with anything inside the organization which interferes with its efficient running. The workmen are entitled to bring up anything which, in their opinion, interferes with that efficient running and to have it discussed. Further, they are entitled to bring up any grievance. Whether the grievance be real or fancied, it is equally dangerous and should be removed. If that is observed, then a works committee is efficient. The author spoke of his visit to the United States and of what he saw in the Ford factory. I also have been to America recently on a similar trip, and I found that, without question, more is produced per unit of labour involved, for the reason that the work is better arranged. A man has always got some job ahead of him. In this country generally a man does not see what his next job is going to be, but in the United States the feeding of the work is better, and so also are the means of production. In an engineering organization the works can well be separated into two distinct parts: (1) the production, and (2) the means of production. The ordinary shop staff whose job it is to look after labour and to see that it is properly controlled and guided should not be made responsible for the means of production.

Mr. G. Hurford: The author has stated that it is very useful to have one meeting a month with the foremen in order to explain the company's point of view. I would point out that it is just as important that the foremen should be allowed to explain their own difficulties, as my experience has shown that they nearly always have more troubles and difficulties than the management. With regard to the balance sheet which the author has brought forward, he says that the cost of selling 1 000 motors is exactly the same as that of 500 motors, but he only allows another £1 000 when he sells 2 000. My contention is that the cost of selling 500 motors is not the same as that of 1 000. There is naturally a reduction; otherwise it would be reasonable to assume that it must cost the same amount to sell 2 000 as it does to sell 500.

Mr. W. F. Higgs: The author refers to the "ca' canny" principle of the worker and shows how this can be eliminated by the management. He also says that the heads of the factories must be students of human nature—pointing out that defects in management originate, to a large extent, in the heads of the firm rather than in the workmen. He also refers to the complex articles manufactured. The only way of overcoming the difficulty is, I believe, by specialization. I do not consider that the electrical industry is specialized to the same extent as kindred industries. The result is that we have got to specialize and confine our energies to a small number of articles. On page 340 the author says: "This was satisfactory in the past when competition was not keen and the margins of profits were much higher." I believe that to be a fallacy, for the reason that in the past men were only competing against men, and to-day we are doing the same. We have additional knowledge certainly, but our competitors also have that. The return on capital over a long period is a sure test of organization. The author has pointed out how his system has considerably reduced the cost of production. I had the unique opportunity of being with two firms manufacturing the same class of article in the same district, employing the same class of labour. For years one firm barely struggled along, whilst the other regularly made 50 per cent profit on its capital, due purely to improved organization. I agree with the author that sufficient attention is not paid to the design of castings. It is surprising how much trouble a man will cause by adding a little projection which in the majority of cases could be eliminated or substituted, a core box being thereby saved. With reference to piecework, there is a leading factory in this country manufacturing switchgear—probably one of the biggest factories in the country—which now adopts day-work and makes as handsome a profit as firms which have adopted piecework. I should like to know if the author is really a firm believer in piecework. He refers on page 344 to the operators working piecework and starting on the job before the price is known. That is not piecework, and herein lies some of the difficulty of organization. Clear drawings undoubtedly constitute the foundation of factory management and works production. I am convinced that sufficient attention is not given in the average electrical factory to this point, particularly in comparison with the petrol-motor industry. With regard to the author's warning as to the Production Department, I consider that the latter can be easily overdone. Much of the trouble in the Production Department can be eliminated if the Design Department refrains from taking $33\frac{1}{3}$ per cent of the time required for delivery. No reference is made in the paper to the importance of detail on lists of material. When the rotary converter to which the author referred is nearly ready for test, it is usually not the spider casting or the shell casting that holds it up, but a trivial matter of two or three rivets. Referring to the different rates of pay of men on machines, I should like to know the author's opinion of the suggestion that the basis of piecework should be time rates instead of money rates.

Mr. Kenelm Edgcumbe: I am pleased to see that the author lays stress on the study of economics. I,

almost look upon this as a more important factor, in many ways, than even committees, and so on, in bringing about good feeling in the works, because however good the feeling on those committees may be, there are bound to be occasions when the management and the men's representatives do not see eye to eye, and it is extraordinarily difficult to put one's case to a man who has had no grounding in the fundamental common-sense of economics. The better class of man, no doubt, has a rough and ready knowledge of the subject, but the average man whom one encounters is lamentably deficient in this respect. This is doubtless due to our modern system of education, rather than to any mental failing. I feel sure that it is time the question of common-sense economics was taken seriously in hand.

Mr. J. R. Cowie: Reference is made in the paper to the Production Department and to the Process Department. These, however, deal with materials, and that brings in the Stores Department, which is not referred to under the main headings of the paper. If the stores have fallen behind, the whole operation is delayed. The other point to which I wish to refer comes under the heading of design. Due to that a works can be stopped altogether, because, as I read it, included thereunder is the actual electrical or mechanical design and the actual drawing-office work, and in some instances of very special items the whole of the delivery time can be spent in these two sections. It seems to me that either the Process Department or the Progress Department must have some correlation with design in its truest sense.

Mr. F. Tremain: I was very gratified to find the importance attached in the paper to the Inspection Department, which branch, in a well-conducted works, is becoming more and more recognized. In my capacity as inspector for the buying side, during a period of about 12 years, I often found opportunities of suggesting to manufacturers methods of economy, and, to my employers, the introduction of modifications in specifications in future jobs, which would reduce the cost —which, of course, the buyer has to pay. I was also glad to see that the author referred to the so-called "finished product" that comes out of our universities. It is deplorable to find so many graduate engineers unable to get a job. I think it is often because their training in many of the technical colleges is too academic, and it should be pointed out to our professors that their curricula as regards engineering training appear to require some modification.

Mr. R. S. Allen: Fig. 1 shows the co-operation between the various sections of the works management, but no reference is made to the Purchasing Department. I consider that to be a very important section of any works, and its absence is indicated in the tables on page 350 showing the costs of various numbers of motors, where the author points out that the material per machine for 2 000 motors is the same as for 500. It seems to me that the Purchasing Department should get a much lower cost for the larger number. On the subject of rate-fixing, the Planning Department fixes the price in the early stages, and the foreman of the department may have both a planing and a milling machine, with either of which an operation may be done. The price being fixed for the less expensive operation, how is the price adjusted for a more expensive? The fact that a youth may be required to do a job which was intended for a man, or vice versa, also requires adjustment. These are difficulties which, I think, militate against the early settlement of prices. It is not by way of criticism that I raise these points, but merely for information, because in many works the price is not fixed before the workman about to do the job asks for it. Can the author state the percentage of office staff to workmen for the Rate-Fixing, Process and Production Departments, as he does for inspectors on page 348? The sinking fund for unemployment is a very admirable conception, but I think that there would be a good deal of difficulty in applying it. Will the individual who is fortunate enough to earn a super-bonus benefit entirely by his work, or will he help to support those who are not so fortunate? On the subject of "ca' canny," the workman is only following the lead set by the employer. If work is not coming in as it should do, and there appears to be only one or two months' work ahead, men are discharged to spread the work over a longer period. This example is followed by the men in order to avoid being discharged. That is the situation for which I can suggest no remedy. Until men understand why it is necessary for the employer to follow the course he does, due to the immense difficulty in re-starting a works once closed, they will, I suppose, continue their present practice. On the subject of inspection, I would ask the author whether the inspectors overlook a man while he is doing his work, say while he is operating on the first few articles, or whether they wait until a batch is completed and therefore possibly have to condemn the lot rather than a few.

Major H. Brown: Is the Institution aware that during the past 5 or 6 years there has been a very appreciable falling off in the facilities for technical education that are open to workmen? In 1918 the Board of Education decided to abandon the examinations in science that they previously had held, and shortly after that the City and Guilds of London Institute followed suit as regards technical subjects. With the exception of examinations in Telegraphy and Telephony, Gas Engineering and, I believe, Electric Wiring, which are continued by special request, the City and Guilds Examinations have ceased. That means that the better class of workman is now unable to produce satisfactory evidence of education beyond the standard of the ordinary council school. There is now no widely recognized technical examining authority in this country between the ordinary council schools and the universities. This is a serious discouragement to the more ambitious workman, and I wonder whether the author has done anything in his works to fill that gap.

Mr. H. W. Richardson: I cordially agree with what the author has said in regard to education. I also agree to some extent with what Mr. Mensforth has said about some workmen not being quite so blind to economics as might seem to be the case at first glance. Usually, however, there are some eight or

ten stock questions which 90 per cent of workmen put, these having been drilled into them by trade union agitators. With reference to Mr. Mensforth's point about 50 per cent of the selling price of goods being absorbed by works costs and the other 50 per cent being regarded by the workmen as profit, I think it is possible to make the majority of workmen realize that such things as distribution costs are essential and that these are bound to account for a proportion of what at first sight seems to them to be profit. In the main there is room for a great deal of improvement in the methods of attempting to give a real grasp of the fundamentals of economics to working men. I do not think that a great deal of educational work is likely to be done by means of lectures. More can be done by individual effort, and it is the duty of those who do get opportunities of speaking to the workmen from time to time to do some real "spade work." We should endeavour to show them what increased production and the lowering of costs really mean; graphical work will be of considerable assistance. In Fig. 1 "Designing" appears to be rather isolated, and I feel that an additional line should be drawn on the diagram connecting it with "Production." In the same way "Designing" might be joined to "Process," so that the former would be linked to other departments as the author really intends it should be. In regard to co-operation, the meetings between the heads of the departments and others must be regular; it is no use having more or less casual meetings. There should also be firm agenda on which the discussions can be based. A previous speaker mentioned the importance of the Buying Department; closely linked with this is the stores. The importance of having these properly laid out, with easy exits and entrances, cannot be over-estimated. In some works the stores are situated behind a pigeon-hole, the men having to form up in a queue and wait, thus involving a great deal of loss. As much space as possible should be devoted to the stores, which should be in very close touch with the Production and Process Departments, particularly the former, so that sufficient notice may be given as to the material required. The transport within a works affects production tremendously. Of late years a certain amount has been done with electric trucks. These are somewhat cumbrous in appearance but very mobile. There is nothing more annoying for a worker than to find, after a particular piece of material for which he has been waiting has been brought on a hand-truck, that he cannot get it on to his machine because the overhead crane is employed elsewhere. In a shop fitted with small auxiliary runways of fairly large radius any delay of that kind is obviated. There is also the question of the arrangement of machines in the workshop, which is very important. The grouping together of too many machines of one class does not tend to efficiency. I think that the best method is to arrange together a few machines of each class necessary for performing the complete series of operations required upon the parts to be dealt with. Then, with the aid of two or three of the auxiliary runways referred to above, a given part can be machined from start to finish with a minimum of handling.

Mr. W. E. Burnand: I can hardly agree with the author's remark on page 340, that "the time is past when a technical business can be run by one man." If he had said that possibly the days of such businesses are numbered, I might be more inclined to agree, but I should not predict the number of days still left for them. In every case, success in running either a big business or a small business depends upon a realization and an efficient utilization of the possibilities of the particular business, and even more so upon a realization of its limitations. To attempt to run a small business on the lines of a large one very quickly results in disaster; and, similarly, to attempt to run a large business on the lines of a small one results in chaos. It would not be possible for me to make machines in a small shop to-day and sell them at a profit, as I am doing, if the larger works were efficiently run and organized. The fact is that even these larger works are in only an incomplete state of development, with many of the handicaps of the small concern as well as the high costs of a large concern, without sufficient output to carry these costs unless they are excessive per machine. Until more efficient standardization is adopted and a large-scale grouping of manufacturing interests effected, making real quantity production possible, electrical manufacturing can only make slow progress through its present awkward stage. In this connection Table 2 is striking, as showing piece-work time based on one article in a large works, and Table 5 gives a good idea of the amount of time taken to obtain material which, however, should be a steady flow not identified with any particular order on really large-scale production. I believe Table 5 to be on sound lines with the present quantities, and that, as stated by a former speaker, Americans owe much of their success to the fact that they plan ahead farther than we do. I entirely agree with the author as to the value of detailed production and process records. Whilst feeling inclined to criticize a number of figures in the tables on pages 350 and 351, taking them as a whole I do not think that they are really such a long way out as might appear on a casual inspection of isolated items. One has to judge a system by the results, and the fact that the author is decreasing the work in progress from 7 to $4\frac{1}{2}$ months is, I think, sufficient proof that the system is a good one. Table 2 affords another illustration of the value of a good load factor. On one of the slides shown during the meeting I noticed that the speed of drills was expressed in revs. per minute. I would suggest the following as an improvement. On each drilling machine I have a card with speeds not specified in revs. per minute, but in certain notches—1, 2, 3 or 4—as correct for holes of various sizes in different materials. Thus, if a man is drilling a $\frac{3}{4}$ in. hole he should use, say, notch 3, but this is not compulsory. I simply say: "That is the right speed for average material," and a man can use that speed or not, but if he is on another speed I want to know the reason, and very often there is a sound reason, such as hard material, or extra depth of hole, both of which have a very great influence on the speed and feed for efficient drilling.

Mr. P. M. Baker (*communicated*): The subject of

the paper—production on a sound economic basis—is one of the greatest importance; it is in fact vital to our economic life. It is, at the same time, a side of their work to which engineers and managers rarely seem to attach sufficient importance. As emphasizing this point I will call the attention of members to the recent articles by Lord Weir (*Times*, 13 January) and Lord Milner (*Observer*, 14 January, *et seq.*) and to the speeches of the Rt. Hon. R. McKenna at the annual general meeting of the London, City and Midland Bank, perusal of which will help us to clarify our ideas on the subject. The author bases his paper, as I read it, on a premise that we can only retrieve our position in the manufacturing world by adopting every possible means for securing cheap and efficient production—a proposition which is so abundantly proved that one marvels at the view escaping any thinking man. It is far from being generally appreciated that economic laws are just as inexorable as physical laws and that legislative tinkering in economic matters, such as the fixing of rates, early closing of shops, etc., can only restrict trade; they cannot alter its economic basis. I am generally in agreement with the author's statements, but there are two points to which I should like to refer. First, I am very doubtful whether anyone connected with the management will be able to lecture very convincingly on economics to the trade unionist. Labour has its own views on economics, truly narrow and short-sighted in most cases, but honestly held and thoroughly believed in by the rank and file. The Communist Party realizes how difficult is the task of converting the adult, and holds Sunday Schools for the education of young Communists, and it is the bounden duty of the saner part of the community to combat this by teaching the elements of citizenship to the youngsters in the shops or indeed before they leave school. Secondly, while agreeing with the author, in the main, I should like to go farther than he in this direction. The training of boys for industry should have two aims:—(*a*) To convert the boy into an efficient workman, training hand and eye to perform operations quickly and accurately with the least possible effort, and at the same time offering him technical education opportunities which will lead to his advancement to the highest position his ability justifies; and (*b*) so to train his thinking and reasoning capacity and to give him such knowledge of affairs and men that life will not become the humdrum, drab existence towards which in these days of automatic and semi-automatic machines it is gravitating: in short, to teach him to live. It is surprising how much can be done and in what a short time in these directions if the work is entrusted to the right type of man, without which it is virtually useless, if not even harmful. The author deals with the more strictly educational aspect of this subject. I should like to see the efficiency of the men increased by the adoption of improved methods of actually training workmen, whether in special factories (as I think best); in "training bays" in charge of suitable instructors; or in the shops themselves. (See my article in *The Times Educational Supplement*, 19 August, 1922.)

Mr. P. G. Pettifor (*communicated*): I agree with the author that all possible steps should be taken to mitigate the dread of unemployment which, especially in times of trade depression, is a very real factor in reducing the efficiency of a workman, but I consider that an unemployment scheme would be more equitable if run by the electrical engineering industry as a whole rather than by isolated firms. Referring to the purchasing specifications, the use and issue of these should be carefully considered in each case. In my experience the use of such specifications has, in some cases, caused the cost of goods supplied to be unnecessarily high. Where everyday commercial products can be used, such specifications are not necessary.

Mr. G. H. Nelson (*in reply*): Referring to Mr. Mensforth's remarks regarding labour's knowledge of economics, there was no intention on my part of patronizing labour; on the contrary, I am anxious to encourage them to study economic questions and I still adhere to the contention in the paper that the majority of the workers have little or no knowledge of economics. This was particularly emphasized when one of the leading members of my works committee (who is also a member of one of the branches of the A.E.U.) passed a remark once at an open meeting that "one could not have prosperity without war." I agree with Mr. Mensforth's remarks that the proportion of labour in the cost of the product is often the smallest item, and I also agree that many factories pay more attention to the examination of the labour cost than to the other components; I therefore fully support his recommendation that equal attention be given to all sections. In regard to the estimating section, this is a part of the Mechanical Process and Rate-Fixing Department. I agree with his remark that a man of average ability should be able to earn 33⅓ per cent bonus upon his basic rate and not upon his wages. This was not made clear in the paper. With regard to the fundamental basis of piecework that "prices must be the subject of agreement and mutual negotiations," this has been overcome in my case by arranging with the works committee to accept the principle and basis on which these prices are fixed. So far we have not come across any cases where disagreement exists beyond the point outlined in the paper. If one should arise it is referred to the management, in accordance with the general principle upon which the works are run, and, as demonstration is provided for, it is not likely to go beyond this stage in a properly managed works.

Mr. Mensforth and other speakers referred to the example given of the effect of increase of production on actual cost of an article. I will therefore deal with the point at this stage. In regard to Mr. Mensforth's remark that the factory expenses go up considerably more than the 25 per cent shown in the paper when the output is doubled, I quite agree with him there, but in the example given in the paper he has apparently overlooked the fact that a certain item of £3 000 for extra night work is shown separately instead of being included in the factory expenses, as it may be in certain cases. The factory expense in the example of the doubled output is therefore 75 per cent on labour, as against 100 per cent with the previous output. In examining the figures of the factory with which I am

associated I find that the figure is more like 66 per cent, including overtime allowances.

With reference to Mr. Hurford's point in connection with selling expenses, although I do not discuss this question in the paper, I would say that from general experience one often finds that, with a small sale, selling expenses go up due to the extra effort that has to be put forward to endeavour to increase sales.

I entirely agree with Mr. Mensforth's remarks on works committees emphasizing the fact that where these committees have failed it has been largely due to the lack of the right sort of leadership by the employer; his recommendation as to the constitution of the works committee coincides with my opinion. In regard to his suggestions in connection with engineering organizations, namely (1) production, (2) means of production, I think the two distinct parts recommended by him are fully covered in the paper.

With regard to Mr. Hurford's remarks *re* foremen's meetings, the foremen are encouraged to speak of their difficulties and the solutions suggested.

Replying to Mr. Higgs, I entirely agree with his recommendation of standardizing and specializing. Unfortunately, however, manufacturers in this country do not co-operate so as to compel the purchaser to accept a standard article, but rather, in order to make sure of effecting a sale, will often promise the customer anything. With regard to his question on piecework, I am a firm believer in piecework, because if day-work is standardized the best worker slows down to the speed of the slowest and special efforts are then necessary to increase the output of the factory by eliminating the slow workers, whereas in piecework the willing worker is on his own merits and can make as much as he likes, and therefore is not affected psychologically. In regard to his query about the basis of piecework, I am of the opinion that this should be time and not money, as this really is the basis of all calculations by the Rate-Fixing Department and the men in the shop. Concerning his remarks *re* the importance of detail on lists of material, it is the business of the Production Department to obtain the whole of the material, including detail parts.

Mr. Cowie asks for further information in connection with the Stores and Designing Departments. The Stores Department should come under the control of the Production Department, who are responsible for the fixing of all ordering levels and quantities and seeing that the material is there when required. The Production Department is also responsible for laying out the programme for the Design Department, i.e. the dates when drawings of various parts are required, and to see that these dates are kept.

Mr. Allen's remarks regarding the Purchasing Department are dealt with in my reply to Mr. Cowie. Referring to Mr. Allen's question *re* the arrangements that are made when operations in the shop are done in a different way from that laid down by the Process Department, this is taken care of by the time-study man in the shop. If the foreman is compelled to make a change in the process of operation for some reason or other, he obtains the services of the time-study man, who refixes the price for the new condition. This is referred to on page 344 of the paper as follows: ". . . or owing to the best machine for the operation not being available, then an additional piecework time fixed by the time-study man is allowed for the job, covering the excess time involved only." Mr. Allen asks for the percentage of office staff to workmen in the Rate-Fixing, Process and Production Departments. These are as follows:—

Department	Percentage of Factory Cost	Percentage of Productive Payroll
Production	0·65	3·4
Technical and Mechanical Process Depts.	0·65	3·4
Inspection and Testing ..	0·65	3·4

Referring to the sinking fund for unemployment, my idea is that each man should benefit by his own effort, and it should not be pooled. In connection with Mr. Allen's remarks regarding inspectors, in the works which I control, the inspectors are overlooking the men's work throughout the operations in the machine and on the floor, and every part is not taken to the inspector at a bench.

Major Brown raises the question of technical education. I may say that we have done all we can to improve the technical knowledge of our employees, but efforts in this direction are chiefly applied to the apprentices.

With regard to Mr. Richardson's remark about connecting up "Designing Department" with "Production" and "Designing" with "Process" in Fig. 1, naturally these departments co-operate very closely together, but I thought it unwise to make the diagram complicated by drawing and connecting up all the departments separately instead of showing them connected through the works management. The mere fact that they are shown connected through the latter, means that they should all co-operate and work together. With regard to the question of transport, this is generally under the control of the works superintendent. Although it is very important, I did not feel it necessary to describe the details. The question of keeping transport down to a minimum was very carefully considered in fixing the shop lay-out.

I entirely agree with Mr. Burnand's remarks regarding the running of a small business, and whereas all the detail which is necessary in a large business would be ruinous to a small one, at the same time I suggest that the same general principles should apply. I also agree with his point *re* efficient standardization. I thank Mr. Burnand for his suggestion that speeds of drills might be expressed in notches on the machine.

Referring to Mr. Baker's communication, I am very pleased to have the opportunity of supporting his contention that every effort should be made to combat the efforts of the Communist party, particularly its activities in the direction of proletarian Sunday Schools. We in our works have endeavoured to meet this by lectures to our boys in working hours, but a great deal more must be done. There are many sound thinking men giving their time to countering the Communists. The basis of the whole matter, as mentioned by Mr. Baker, is the teaching of the elements of citizenship and sportsmanship. After all no real sportsman can be a Communist.

North-Western Centre, at Manchester, 23 January, 1923.

Mr. W. J. Medlyn : With the intensive development of industry and the mechanical aids to industry, scientific management is a subject of increasing importance, because where large numbers of men are employed the opportunities and possibilities of waste due to misdirected effort and lack of co-ordination or co-operation between the different departments are correspondingly great. One writer has stated that "the efficient utilization of labour will often overcome the handicap of poor equipment, and an engineer can have no greater asset than the aptitude to handle labour efficiently." This view agrees with one of the points made in the paper. I am not speaking with experience of ordinary industrial works, but in the South Lancashire District of the Post Office Engineering Department we have close on 2 000 workmen employed in the construction and maintenance of telephone and telegraph plant, and in a matter of this kind, although we are a Government Department, we are subject to the same economic laws and conditions which apply to a private industrial undertaking. We have a system of costing as regards the number of units of plant of various kinds which are constructed or maintained, but the organization required in a factory would not be applicable to our workmen, who generally have to be employed in more or less isolated small groups over a relatively wide area. It may be matter of common interest to mention that it was our practice some years ago to show these labour costs in terms of money values. The arrangement worked quite satisfactorily when the labour rates of pay remained fairly constant over a long period of time; but, following upon the outbreak of war, the rates fluctuated so much that it became impracticable to compare costs on that basis from year to year or over a number of years. I have no doubt that that condition would also apply generally to ordinary works management. The author stated that his firm's present practice is to use the man-hour basis of comparison. We overcame our difficulty in the same way; that is, our operations are now measured in terms of man-hours as well as money values. The author has referred to the advantages gained by a system of vocational training of workmen. In the Post Office we have this system in practice to a considerable extent, in co-operation with the local educational authorities. Evening classes are formed, and the student normally attends twice a week. One evening is devoted to the teaching of the elementary theory of the subject, and the second evening to the teaching of the correct method of carrying out the practical work on which the student is normally employed. The students attend in their own time, but their railway fares (or tram fares) and class fees are paid by the Post Office. We have had these classes running successfully in Manchester and Liverpool, as well as in other parts of the country, for several years past. Taking the figures for the whole of the country, 1 364 students attended the classes during the session 1921–22, and 629, i.e. about 50 per cent, were awarded proficiency certificates. The cost was £1 3s. 6d. per student. In connection with the extension of our underground cable system we have required large numbers of cable jointers, and, as the ordinary step-by-step advancement was not rapid enough for this special requirement, we met the want by establishing jointing classes which the men attended in the department's time. In addition, pamphlets of an elementary and practical character covering every phase of the technical work carried out by the department have been printed, and such of those pamphlets as have a bearing upon a man's work are issued to him free of charge; 67 of these booklets, dealing with different subjects, have been issued, and altogether some thousands of copies have been distributed. It is interesting to note that those pamphlets are, in principle, somewhat similar to the works specifications which the author has explained. The pamphlets tell the man exactly what is the proper way of carrying out his work. Of course they are not quite so simple as the charts that were put upon the screen, but the principle is, I think, just the same. The drafting of these pamphlets was initiated by the Engineer-in-Chief of the Post Office at the end of the war. He called for volunteers among the members of the supervising staff who were experts in the various subjects; and, as a result of co-operative effort, the great bulk of the work was completed in about a year.

Mr. G. E. Bailey : The author has pointed out that, if we are to meet the world competition, it is necessary that all sections of an industrial organization should co-operate. I should like to go further and say that the firms should co-operate more than they do at the present time; in fact, they should do what they did during the war. Generally speaking, I agree with the author's views put forward in the paper. I recently attended a meeting where Mr. Brownlie, Chairman of the Amalgamated Engineers' Union, admitted that "ca' canny" was quite prevalent and that he himself had practised it. He went on to demonstrate that this was justified, and to point out to the employers that the remedy was largely in their own hands. In his opinion the chief cause was the workman's fear of unemployment. The author has put forward a scheme for dealing with this which has many good features, but I cannot say that it is going to meet the whole of the trouble. In the first place, his plan appears to depend absolutely on the super-bonus. Now it is common knowledge that generally (excluding special periods of unemployment such as we have now) the unemployed are the inefficient workers; so that, unfortunately, these people would not have been able to contribute towards the unemployment fund. Unless super-bonus went into a pool I do not quite see how the inefficient would benefit. I think that there is probably a lot to be gained by unemployment insurance by industry. This has been discussed by the Employers' Federation and it has been discussed by the unions, and I hope that shortly a concrete scheme will be put before us. I appreciate that it is a very difficult subject and the chief point will be,

that whilst it enables a man to maintain his efficiency during unemployment it must also guard against malingering. The author points out the importance of co-operation between the drawing office and the works. I absolutely agree with that and I should like to go further. He referred to the effect upon manufacturing costs produced by lack of co-operation between these departments. Later on, unconsciously, he gave a very good lead. He pointed out in the production chart that the only unknown quantity was the first stage—obtaining the material. Obviously the obtaining of material depends to a great extent upon when it is ordered, and here I think is a clue which can be enlarged upon. Lack of co-operation between these two departments will result in information being supplied to the shops late, in the wrong sequence and intermittently and will, in turn, be responsible for late deliveries and increased work in progress. In connection with the foremen's meetings I should like to bring this out, that one of the chief advantages of these meetings is that the superintendent or the works manager gets the whole of his team together; he has representatives of every class of labour, and they sit down and discuss amongst themselves their own particular troubles—production, rate-fixing, labour questions, in fact everything that affects the efficiency of the workshop. In this way each department can compete, in a friendly way, with other departments for the purpose of obtaining the highest efficiency. In connection with rate-fixing, the author pointed out that all rates were fixed in the office. That is quite right for repetition work, but in a general shop it is impossible. I take it that in such a case the rate-fixer would fix prices in the workshop. There again he must satisfy himself that the methods available are the very best. If not, he should take it up at once with the other section, the Process Department, and have the job processed with a view to improving the efficiency and cutting down the cost of manufacture. On production I agree with the author except that I think he does not emphasize quite sufficiently that the improvement of any system of production depends absolutely upon the personal element. It depends upon the various departments and members of the staff honouring promises which they have made. Now, many systems can be evolved, many equally good, but all will fail without this co-operation and honouring of promises. Inspection generally is looked upon as seeing that the very best job is sent out, but I do not think that that is exactly the case. As a matter of fact the Inspection Department could sometimes save a lot of money by seeing that too good a job is not sent out. That may sound paradoxical, but the works must be run on commercial lines. As a matter of fact one of the chief reasons for the adoption of a limit system is that a man may not put too good a finish upon a particular job. He works to the limit that the designer fixes, based on his knowledge of what class of finish is necessary. If a 0·010-inch limit is good enough, it is waste of money for a workman to get down to 0·001 inch. That is where the inspector often comes in. Having agreed with the author on a good many things I am now going to disagree with him. He showed a chart illustrating how profits can be increased by 400 per cent. It is a very attractive scheme and I agree with the result, but I do not accept the methods of arriving at it. He did not explain the chart on the screen in the same way that he does in the paper. In the latter he compares moderate management in the workshop, bad management in the workshop, and efficient management in the workshop; but the total result, of course, is a combination of the whole work of the whole staff including the salesmen. I think that this is really meant by the author as a sort of camouflage bouquet for the Sales Department, because he demonstrates that the whole of the results obtained are due to the salesmen. I find that in the case of the 2 000-motor output the factory cost is £31 5s. and in the case of the 1 000 output it is only £32, so that there is only a difference of 15s. between the two shops. When we compare the final result it is £39 against £44, and the majority of that is made by the salesman, who sells 2 000 motors for £9 000 while the other sells only 1 000 for £0 000. I agree with the results, but in the way they are shown the whole of the blame is put on the shop as usual.

Mr. L. H. A. Carr: Before dealing in detail with specific points mentioned in the paper I would suggest that, taking the subject generally, one part of the question has not really been dealt with, namely, the question of works of medium or small size, of which there is quite a number in this country. In a works turning out a couple of thousand machines a year, say about 50 000 h.p., or even in a smaller works, it is probably impossible to use in its full extent a system such as that outlined in the paper. Such works need much more simplified systems. To take a single example, some reasons why they cannot go in for the Hollerith system were given in Mr. Lawrence's paper before the North-Western Students' Section last winter.* A small firm has one or two advantages which are lost in a large one. It is much easier to keep track of things, and also it is easier to bring the designers well into contact with, and more into a position of responsibility for, the various technical processes that have to be dealt with, the buying of materials, etc. That this lack of contact has been found to be a difficulty in large firms can be inferred from the fact that the author has so largely brought out the necessity for co-operation between the experts in the various departments concerned. But in any case the designer must have a good knowledge of all the technical processes and of the materials used. The excellence of a designer may, perhaps, be described as the amount which he knows of these other experts' jobs so that he is able to go the right way to meet them. In Fig. 1 several lines of co-operation are omitted. Perhaps that was in order not to make the diagram unwieldy, but the Technical Process Department and the Inspection Department must both work in co-operation with the designer. Another point which has scarcely been dealt with in the paper, but has rather been taken for granted, is the importance of the goods being right. It is no use having a works where things can be manufactured beautifully and

* *Journal I.E.E.*, 1923, vol. 61, p. 52.

cheaply and salesmen who can sell them, if the job is not right when it is done. Although the author has mentioned some of the attributes which he thinks a works manager should possess, he appears to have taken it for granted that the designer is absolutely perfect. In costing, an important point which has to be watched is the accuracy with which the work-people in the shop book their time on the right job. Inaccuracy in that respect has in the past caused trouble in working out a good many costs. It is essential that the men in the shop should put the costs down to the right job, because that is really the foundation of the costing system. If that is not done no cost system can give correct results. The author has given us a case where a bracket was improved by co-operation. Personally I am inclined to say that the designer was to a large extent responsible for turning out a poor design. If he did not know what was the best design it was his business to find out by co-operation. Such faults may be overcome to a certain extent by utilizing better-class men, and the whole question of what quality of engineers and draughtsmen are used for certain jobs is mixed up with this question. If all engineers and draughtsmen were perfect there would not be nearly so many troubles, but the majority are not perfect. Possibly salaries are not sufficient. One cannot always afford to put the best class of man on some of the smaller work, and in design offices it would appear to be necessary to balance the amount that can be spent on the staff against the cost of the mistakes which a less-skilled staff will make. In regard to the question of committees it must not be overlooked that whatever committees are formed, they must be set up in such a fashion as not to destroy responsibility. Responsibility for any job must still be kept in the right place. On page 341 the author has said: "Success depends largely on one's executive acumen, initiative and ability to co-operate." I would add that, in addition, hard work is absolutely necessary. With regard to the accusation that the designer sometimes fails to give to the works full information by the date required by the Production Department, that is very often the customer's fault. I would suggest to members who may have to influence orders, or are consulted with regard to orders, that they can get much better service if they will give all the necessary information when the order is placed. The type of thing I have in mind is the case where a consulting engineer will not settle what cables he is going to have until the job is nearly finished, his attitude being: "It does not matter, the terminal box is the last bit which will be put on the machine." It does matter. It holds up the whole business, the drawing office cannot complete their part of the work, neither can those responsible for ordering the material. I think that probably those outside manufacturers' works cannot have any conception of the extra work and worry on their particular orders if information is held back like that. The lay-out of the shop has not been discussed in the paper? Needless to say, it is of great importance. Further, however well the shop may be laid out when it is first built, extensions and alterations are almost bound to take place afterwards. It is to be regretted that this question has not been dealt with in the paper. The author has not dealt with the difficulty of arranging that the work which comes into the shop does not include too high a proportion of machines of a particular type. For example, a large machine tool may be sufficient to deal in a year with an average year's work. But suppose all the orders necessitating the use of that machine tool are not spread over the whole year, but happen to be received in a single month; would the tool be sufficient?

Mr. A. B. Mallinson: To my mind the personal element is one of the most important factors in the whole thing, and I think that in Fig. 3 the author has unconsciously shown a very clear example of the personal element as it exists. That figure shows four curves, and we find in each a drop in production for July. That, I think we can assume, is due to holiday stoppages. The surprising thing, however, is that the dotted line showing the rejects is practically steady. There we have got the personal element. The amount of work coming before the tester has decreased; therefore he inspects rather more thoroughly and the result is a straight line. Another point that I have come up against very often, and upon which manufacturers feel very strongly, has only been casually mentioned in the paper. When we have got a job completed we want to get it out of the works at once. Do not let the workman see it standing about for some time if he has been told that it was wanted in a hurry. During all the time that the job is going through there is need for co-operation between the salesman and those who are working to get the job completed in a promised number of weeks. I would emphasize the great importance of good feeling between master and men, and particularly between every department of staff. As the author has pointed out in one of the slides, it is the saving on the whole job that tells at the finish. Although the amount may be very small in each individual operation, they all count up in the end, and it is that which enables the seller to influence the customer and secure the order.

Mr. R. Townend: Having had some experience of the actual working of the system of works production described in the paper, I can agree with the author as to its advantages, but of course the extent to which it can be adopted depends largely upon the size of the factory. I fully agree that the closest co-operation is necessary between the engineering department, drawing office and shops, if economical production is to be obtained, and the lack of this co-operation is illustrated by the example of the motor end-bracket mentioned by the author. It would appear at first sight that the responsibility for the complicated design rested upon the draughtsman, but I consider the pattern-maker to be even more to blame. The former did not appreciate that the design was complicated, but the latter knew that it was, and ought to have taken steps to have the design simplified. Whilst I agree that in the case of complicated designs it is necessary that these should be considered at a meeting of the designer and manufacturer, it would be quite impossible to apply this to each part of a piece of apparatus, as advocated by the author.

Mr. T. E. Herbert: Some ten years ago I submitted a paper on scientific management to the Institution of Post Office Electrical Engineers and the time which has elapsed has confirmed my opinion, for what it is worth, that the basic principles are unassailable. The present paper may be described, I think, as a description of the author's methods of applying scientific management to his works' problems. Taking a really broad view of the subject, I think he has laid down a few fundamental propositions which, if carried into effect, will produce the organization he has described. Such fundamental principles seem to me to be those of Dr. Taylor. First of all, functional organization, secondly, process instructions, which obviously involve time and motion study, and thirdly the time-table. I should imagine that the time-table is one of the most important things; so far as my problems are concerned it is undoubtedly so. The main object I take it is to obtain the maximum results with the least effort, which is merely another definition of efficiency, or alternatively the elimination of waste. The human element of the problem is rightly stressed, and the absolute necessity of obtaining full co-operation is appreciated. It seems to me that the human element is dealt with by a system of payment by results, and an endeavour to eliminate suspicion by dealing quite openly and quite fairly with the worker, but I would venture at this point to offer a word of friendly criticism. I am disposed to think some of the author's introductory remarks are of somewhat doubtful validity, and that the argument should have been carried a good deal further or he should merely have taken his stand upon getting results with the minimum of effort, in other words on the attainment of efficiency. For example, some of his remarks are in conflict with the teaching of the Manchester School of Economics in regard to buying in the cheapest market and selling in the dearest. If that principle, so stated, is sound the worker ought to give as little as he dare for as much as he can possibly exact. Either both those propositions are sound or they are both unsound. I do not propose to carry that point any further, but I would say that the fascination of the fundamental idea of Taylor's system to me is that it is a practical method of substituting co-operation and help for the mere driving methods which have been so unintelligently adopted in a good many factories in the past, and perhaps even to-day. Here again I am convinced that the true rectification of most of our troubles lies in the attainment of efficiency in general. Some remarks have been made on selling efficiency, but not merely do we want efficiency in the factory, we also want it in finance and in distribution. I will not pursue that subject further, but I will suggest that nothing essentially wrong can persist, and that waste seems to be the deadly sin which carries the most severe penalties. I would ask the author to look at the appalling inefficiency of finance and distribution and appreciate that the engineer has a problem to solve which nobody else seems to be willing to tackle. That is why the remarks recently made by the President, and reiterated in this paper, on the study of economics are of such vast importance. It is of little use to obtain splendid results in the factory if the other processes are scandalously inefficient. One speaker touched upon the point that cost accounting, which involves an elaborate system of records, depends on the accuracy with which the worker fills up his time sheet or whatever equivalent is in use. I was rather interested to realize that we were not the only people who had a certain amount of difficulty in getting precisely accurate information on bits of processes. The Whitley Committee has helped us in those matters by impressing on the members of the staff the desirability and the reason why we want these things in detail. These committees have, too, been exceedingly valuable to us in removing suspicion and in attaining that healthy spirit of cheerful co-operation which is the goal of the much-maligned idealist.

Mr. G. H. Nelson (*in reply*): I was very pleased to have Mr. Medlyn's contribution to the discussion, and was particularly gratified to know that a Government department has established a system somewhat on the lines of that outlined in the paper.

With regard to Mr. Bailey's comments, I heartily endorse his suggestion that in addition to the co-operation inside an industrial organization, it should extend outside between firms. I may say that during my visit to the States recently I found this very prevalent and was particularly struck with the free way in which I was taken round the American works and had various processes explained to me, in spite of the fact that I represented a competitor. I endeavoured to give *quid pro quo*, I consider it the duty of all Englishmen who visit the States to deal with the Americans in this frank manner, as by this the feeling between the countries can be improved considerably and the power of America and England together increased and directed in the way of preventing a recurrence of calamities of the terrible nature of the Great War, which after all is the real cause of the suffering and unemployment at the present time.

In connection with unemployment, I agree with Mr. Bailey that the Government scheme of unemployment insurance by industry is sound, and I do not suggest that the scheme outlined in my paper should replace this, but it should be in addition to the Government scheme, the latter being that which is necessary to enable men to exist when out of work, whereas my scheme is with the object of encouraging men to work and give their best to provide something in addition to Government allowance. In connection with the Rate-Fixing Department, in the works with which I am connected the whole of the drawings—even for odd jobs—go to the Rate-Fixing Department and are processed. This does not just refer to repetition work, as suggested by Mr. Bailey. I am sorry that he does not think that I emphasized sufficiently the personal element. There is no doubt that the success of any system in a works is absolutely dependent on the human element. No matter how good the system is, if the will to work is not there it will be a failure, and the object of works committees, foremen's meetings, and the careful selection of heads of departments, as emphasized in the paper, is the endeavour on the part of the manager to get the team of the best personnel to co-operate and make the

system a success. In connection with the necessity of seeing that too good a job is not made, we endeavour to take care of this in the Rate-Fixing Department by specifying on the process sheet the class of finish that is required, and the price is fixed accordingly. In addition, as mentioned in the paper, we mark our drawings with different colours, to show the differences in finish. With regard to Mr. Bailey's remarks regarding the credit for increased output going to the salesmen, I am afraid that I rather look at the question from the opposite view, namely, that the works are so efficiently run that it is not possible to make any great improvement, whereas by ensuring that we get the proper results from the necessary selling expenditure, great economies arise.

In connection with Mr. Carr's remarks regarding the running of small works, I must say from my experience of large works that I am of the opinion that small works run on the same basic principles, as outlined in the paper, can obtain greater efficiency than the larger organizations, the reason being that the number of personal elements is smaller and therefore more easy to handle. As mentioned before, I still feel that the same principles should be applied, with of course the application of the right common-sense of the management as to the details required. With regard to the booking of time in the shop, I agree with Mr. Carr that it is difficult to get 100 per cent efficiency in this direction, but this is taken care of by arranging for a clerk to book all the details on the time sheet under the control of the Rate-Fixing Department and the man only fills in the time. I am glad that Mr. Carr agrees with my view that the Design Department should co-operate as far as possible with all people likely to be interested in the design of a machine. I agree with his remarks in regard to responsibility. On no account must responsibility be divided by the committee system. It is very easy for it to become so, but the insistence on this by the management can prevent it. For instance, in the works where this system is in operation the foreman is not allowed to try to shelve the responsibility for bad work on to the Inspection Department. It is solely the foreman's mistake for having allowed the bad work to be produced. I agree with Mr. Carr that customers can help very considerably by giving full information when the order is placed and by immediately giving a decision in regard to any question which may arise. The matter of shop lay-outs has not been discussed in the paper, because my object has been rather to describe a system than to go into the details of a lay-out, and to encourage existing works to install the system where plant already is in operation, rather than to deal with new factories where the plant can be laid out for ideal conditions. On the other hand, however, even a shop laid out ideally to-day may not necessarily be ideal for the product manufactured in 20 years' time. In connection with Mr. Carr's remark regarding the laying-out of various operations in the shop, the system outlined in the paper enables this to be done very conveniently, because by assembling charts (similar to Table 3) of all the machines produced in any month and so arriving at the total number of machining hours, one can see ahead whether the plant can deal with the output it has to produce, and, if not, then steps can be taken to get outside help where the shortage of machinery exists.

I was glad to hear Mr. Mallinson's recommendation that customers should endeavour to take plant at the time it is completed, especially when they insist on their delivery date. Unfortunately, we have found in many cases that a purchaser has been most emphatic about his delivery date, special pressure has been put on all departments to keep this date, and when it has been kept the machine has remained in the shop for weeks and sometimes months. Customers should realize that the moral effect is very bad.

Referring to Mr. Herbert's contribution to the discussion, I notice that he mentions the principles of Dr. Taylor, who, in my opinion, unfortunately calls this system "scientific management." The bare mention of the word "scientific" frightens a great many of the old-fashioned type of employer. That is one reason why this word is left entirely out of the paper. I also support Mr. Herbert's contention that we want efficiency in finance and distribution, and I trust that some experts on these subjects will give us the benefit of their recommendations, as suggested in the paper.

In conclusion I should like to thank all those who have taken part in the discussions for their constructive suggestions, and I sincerely hope that the object which I had in giving the paper will be fulfilled, namely, that those responsible for the management of works will consider such general principles outlined in the paper as are applicable to their own works and apply them where they do not exist, thus helping to reduce production costs and to develop industry, which will eventually result in a considerable reduction of unemployment.

THE RATING OF CABLES FOR INTERMITTENT OR FLUCTUATING LOADS.*

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SUMMARY.

The extent to which the rating of a cable is affected by an intermittent or fluctuating load as compared with continuous running conditions is investigated theoretically, and formulæ are given by means of which the effect of any type of loading can be calculated.

It is shown by experimental determinations on various sizes and types of cables that the thermal time-constant can be calculated either from a heating or cooling curve of a particular cable, or from the specific heat and mass of the various components of the cable.

Tables are given showing the rating for the cables for which load tables are given in the I.E.E. Wiring Rules, on the same basis as for motors, i.e. ½-hour and 1-hour ratings.

The question of the permissible current in cables used for supplying motors or other gear for such purposes as cranes, winches or hoists where the period of full-load current may be comparatively short, alternating with periods when the motor is running light or is shut down, was raised by the Ship Electrical Equipment Committee of the Institution.

Goldschmidt † investigated the case of motors used for such work, and stated that long experience in actual practice has proved that in nearly every case a motor which stands a 1-hour test with a moderate temperature-rise is large enough for crane work. In modern practice, motors for such purposes are rated at ½ hour and 1 hour, depending on the conditions of use.

In the case of cables the time required to attain the maximum temperature is, as a rule, very much shorter than with motors, and it is necessary to consider them separately in order to ensure that the combination of motor and cable will be suitable for a given purpose.

In a previous paper (*Journal I.E.E.*, 1911, vol. 47, p. 711) the authors gave some results showing the order of increased rating that could be used for cables under intermittent load, the periods of variation being a few minutes, as would be the case in the actual use of a motor. These and other observations have been used in what follows.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Journal I.E.E.*, 1905, vol. 34, p. 660.

For the mathematical treatment of the problem let:—

w = rate (in watts) of heat transmission through unit length of the covering of the cable for each degree C. of temperature excess above the surrounding air;

c = heat capacity of unit length of cable per degree C. in watt-second units (joules);

q (or Q) = rate (in watts) at which energy is being developed in unit length of the cable;

θ = temperature excess (referred to in the calculations below, for brevity, as "temperature");

t = time in seconds.

Then, if we assume that the heat dissipation is proportional to the temperature excess at any moment:—

$$qdt = cd\theta + w\theta dt$$

or

$$\left(\frac{w}{c}\right)dt = \frac{d\theta}{(q/w - \theta)}$$

Integrating, $$\left(\frac{w}{c}\right)t = -\log_e(\theta - q/w) + \log_e P$$

where P = a constant of integration;

whence $$e^{wt/c} = \frac{P}{\theta - q/w}$$

To find P, assume that when $t = 0$ the temperature θ has the initial value θ_1, then

$$P = \theta_1 - q/w$$

$$e^{wt/c} = \frac{q/w - \theta_1}{q/w - \theta}$$

whence $$\theta = e^{-wt/c}(\theta_1 - q/w) + q/w$$

If the cable runs for a seconds at Q watts, starting at an initial temperature θ_2, let the temperature attained be

$$\theta_1 = e^{-wa/c}(\theta_2 - Q/w) + Q/w$$

If the cable then runs for b seconds at q watts, starting at an initial temperature θ_1, let the temperature attained be

$$\theta_3 = e^{-wb/c}(\theta_1 - q/w) + q/w$$

and if then $\theta_3 = \theta_2$ we have

$$\theta_1 = \frac{(Q/w)(1 - e^{-wa/c}) + (q/w)(1 - e^{-wb/c})e^{-wa/c}}{1 - e^{-(a+b)w/c}}$$

Or, since $Q/w = M$, the maximum temperature attained when running continuously at Q watts, and $q/w = m$, the maximum temperature attained when running con-

tinuously at q watts, and writing γ for c/w, where γ is the thermal time-constant of the cable,

$$\theta_1 = \frac{M(1 - e^{-a/\gamma}) + m(1 - e^{-b/\gamma})e^{-a/\gamma}}{1 - e^{-(a+b)/\gamma}}$$

Taking the case of a cable running under crane-load conditions where the motor runs at full load for a minutes and at light load for b minutes, and so on, intermittently for a long period, the increased rating for the same temperature-rise as would be attained if the cable were loaded continuously at its normal continuous rating of I amperes, can be calculated as follows :—

Let i be the current on light load and si the maximum load current, s being the ratio of the maximum to the light-load current.

Taking the general case of temperature elevation under a fluctuating load of this kind, we have

$$\theta = \frac{M(1 - e^{-a/\gamma}) + m(1 - e^{-b/\gamma})e^{-a/\gamma}}{1 - e^{-(a+b)/\gamma}}$$

If the watts developed by i amperes be $q = i^2r$, where r is the resistance of unit length of cable at the maximum temperature, then with si amperes the watts developed will be $q = s^2i^2r$. We have therefore

$$M = \frac{s^2i^2r}{w} \quad \text{and} \quad m = \frac{i^2r}{w}$$

and the maximum temperature elevation will be

$$\theta = \frac{i^2r}{w}\left[\frac{s^2(1 - e^{-a/\gamma}) + (1 - e^{-b/\gamma})e^{-a/\gamma}}{1 - e^{-(a+b)/\gamma}}\right]$$

The maximum temperature elevation for continuous running with I amperes will be I^2r/w, and this must equal θ, whence we obtain—

$$si = Is\sqrt{\left[\frac{1 - e^{-(a+b)/\gamma}}{s^2(1 - e^{-a/\gamma}) + (1 - e^{-b/\gamma})e^{-a/\gamma}}\right]}$$

or if $si = nI$, where n is the rating factor, we have

$$n = s\sqrt{\left[\frac{1 - e^{-(a+b)/\gamma}}{s^2(1 - e^{-a/\gamma}) + (1 - e^{-b/\gamma})e^{-a/\gamma}}\right]}$$

Thus, if the cable were rated to run at 200 ($= I$) and if $a = 4$ minutes (240 secs.), $b = 6$ minutes (360 secs.), $\gamma = 1\,300$ seconds, and $s = 2$, then

$$n = 2\sqrt{\left[\frac{1-e^{-600/1\,300}}{2^2(1-e^{-240/1\,300}) + (1-e^{-360/1\,300})e^{-240/1\,300}}\right]}$$

$= 1{\cdot}304$, and the maximum permissible current during the full-load period is

$$si = 1{\cdot}304 \times 200 = 261 \text{ amps.}$$

A simpler problem arises out of the decision of the I.E.E. Committee that cables should be rated on the same basis as the motors used, i.e. at a $\frac{1}{2}$-hour and 1-hour rating. For the calculation of the rating factor to suit these conditions only the initial part of the appropriate heating curve need be considered.

On the assumptions made, the temperature of a cable as deduced from the general equation, at any time t after switching on, will be

$$\theta = M(1 - e^{-t/\gamma})$$

where M is the maximum final temperature.

Let M_0 be the final permissible maximum temperature attained when running with the rated current I_0. To a first approximation

$$M_0/M = (I_0/I)^2$$

therefore $$\theta = M_0(I/I_0)^2(1 - e^{-t/\gamma})$$

whence $$I = \frac{I_0\sqrt{(\theta/M_0)}}{\sqrt{(1 - e^{-t/\gamma})}}$$

If I is greater than I_0, but θ, the temperature attained after the interval t, is not to exceed M_0, we have for the rating factor n :—

$$I = I_0\frac{1}{\sqrt{(1 - e^{-t/\gamma})}}$$

or $$n = \frac{1}{\sqrt{(1 - e^{-t/\gamma})}}$$

For the $\frac{1}{2}$-hour rating, t is 1 800 seconds, and for the 1-hour rating, 3 600.

It will be seen that these formulæ require that the thermal time-constant γ should be known. This quantity is the ratio of the heat capacity of the cable to the rate at which heat, measured in the same units, would be transmitted from the cable if the temperature excess were 1 degree C. Regarded from another point of view it is the time that would be required for the cable to reach the maximum temperature corresponding to any current if, with this current passing through the cable, all dissipation of heat to external space were prevented and the heat generated by the current were applied solely to heating the cable.

Thus, if M be the maximum temperature excess attained when the current is running at Q watts, and if c be the heat required to raise the temperature of the cable 1 degree C., then the heat capacity of the cable when raised in temperature M degrees is Mc. When it has reached its maximum temperature corresponding to the current carried, and conditions have in consequence become stationary, the heat dissipated per second by the cable, wM, is equal to the heat generated, i.e.

$$wM = Q = I^2r$$

where r is the resistance and I the current. Therefore the time required to reach the maximum temperature M, if no heat were radiated from the cable, would be

$$\frac{Mc}{Q} = \frac{Mc}{Mw} = \frac{c}{w} = \gamma$$

a quantity which is therefore defined as the "thermal time-constant" since it will be the same whatever maximum temperature be considered.

The thermal time-constant of a cable can, therefore, be approximately calculated if we know the weight and specific heats of its various components and the final temperature-rise corresponding to a given current.

The temperature of the core will be generally higher than that of the surrounding layers of insulating and other materials. If in order to simplify the calculation it be assumed that the whole of the cable attains the temperature of the core, it would seem as if the value of the thermal time-constant calculated on this assumption should be somewhat in excess of its true value. This error would, however, appear to be very largely compensated for by the fact that in practice a cable is not freely suspended in air, but is in immediate contact with some support, which also shares to some extent in the temperature-rise of the cable. A comparison of the results obtained by calculation of the constant from the dimensions and thermal quantities

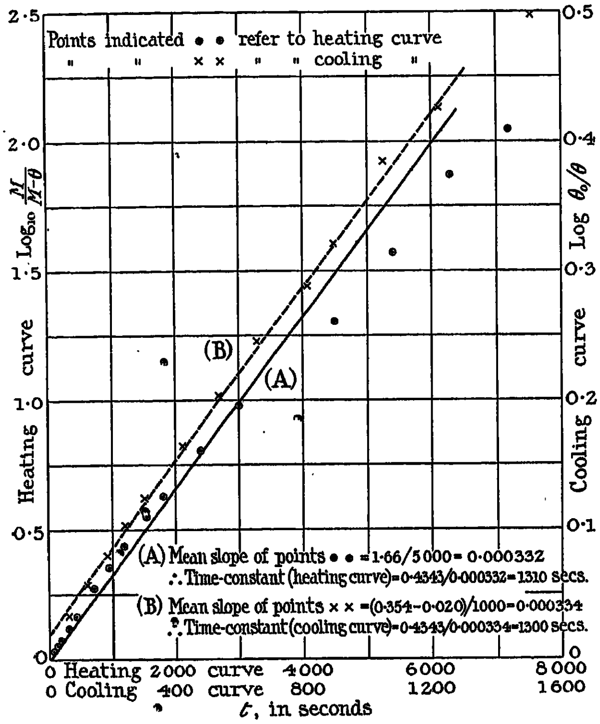

FIG. 1.—Determination of the time-constant of a 19/14 S.W.G. rubber-covered cable by means of the heating and cooling curves.

of the cable with those obtained by the more direct experimental method next to be described would seem to indicate that, within the limits of accuracy required in the evaluation of the constant, the first method affords a satisfactory approximation.

For the calculation of the thermal time-constant from the heating curve we can proceed as follows :—

Since at any time t after switching on, the temperature excess

$$\theta = M(1 - e^{-t/\gamma})$$

where M, as before, is the final maximum temperature, we have

$$\log_{10}\left(\frac{M}{M-\theta}\right) = t\frac{(0\cdot4343)}{\gamma}$$

If a series of values of θ are available for various time intervals after switching on, and if we know M the maximum final temperature, then, on plotting the values of $\log_{10}[M/(M-\theta)]$ derived from the values of θ, against corresponding values of t, we should obtain a straight line passing through the origin, the slope of which line should be equal to $0\cdot4343/\gamma$. This affords a criterion as to how nearly the heating curve follows the exponential law here assumed, and also, if the slope be measured in the proper units, a means of evaluating the constant γ.

In practice, however, this particular method is somewhat difficult in application. Values derived from the first part of the heating curve are liable to error because here the temperature is changing very quickly. In the initial stages of the heating curve the temperature of the core will also be considerably higher than that of the covering, and this would tend to make the value of the thermal time-constant derived from this part of the curve too low.

For the latter part of the curve when θ is approaching its limiting value M, the term $(M-\theta)/\theta$ becomes

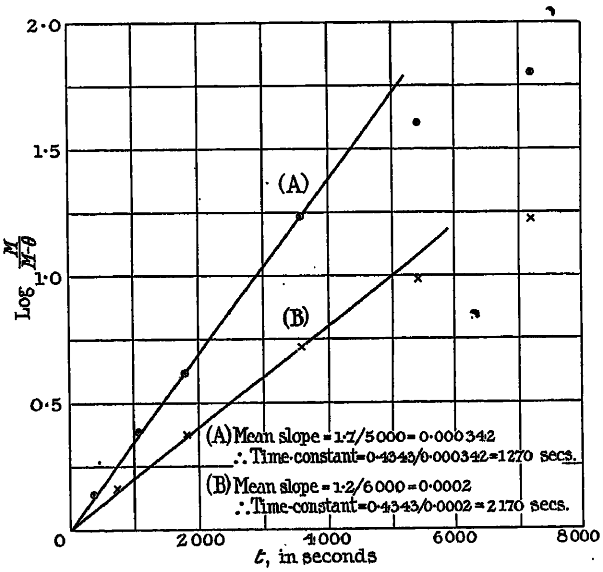

FIG. 2.—Determination of the time-constant of two lead-covered paper-insulated cables :

(A) 0·1 sq. in. single. (B) 0·1 sq. in. concentric.

uncertain, since $(M-\theta)$ is the difference of two nearly equal quantities, one of which, M, requires a very long and careful observation for its exact determination.

For this reason, therefore, it is preferable to use the cooling curve. For this we have $\theta = \theta_0 e^{-t/\gamma}$, where θ_0 is the initial temperature for $t = 0$. From this it follows that

$$\log_{10}(\theta_0/\theta) = (t/\gamma)\log_{10}e = 0\cdot4343t/\gamma$$

so that if a series of values of $\log_{10}(\theta_0/\theta)$ be plotted against t, a straight line passing through the origin should be obtained the slope of which should again be equal to $0\cdot4343/\gamma$.

As this does not necessitate the determination of the maximum temperature it is generally the more convenient method.

Some illustrative examples of these three methods of determining the thermal time-constant will now be given. They will also serve to show the sort of consistency obtainable by the various methods and to what extent it is permissible to rely on a calculation of the thermal time-constant derived from the dimensions and specific heat of the cable in place of determinations based on the characteristics of the heating or cooling curves as obtained by direct experiment.

Example (1). *A rubber-covered* 0·094-*sq. in. cable.*—In Fig. 1 the values of $\log_{10}[M/(M-\theta)]$ are shown plotted against time for (A) the heating curve, and of $\log_{10}(\theta_0/\theta)$ for (B) the cooling curve.

The slope of the best mean straight line through these points has been measured and the constant, γ, obtained by dividing 0·4343 by the slope. The values are :—

(*a*) Heating curve $\gamma = 1\,310$ seconds.
(*b*) Cooling curve $\gamma = 1\,300$ seconds.

The evaluation of the thermal time-constant of this cable by means of the dimensions and specific heat is as follows :—

The total heat capacity of the cable is here the sum of two components :—

(1) The heat capacity of the conductor based on weight of copper × specific heat = 2·135 watt-seconds.
(2) The heat capacity of the covering, rubber and braiding = 2·79 watt-seconds.

Hence c, the total heat capacity per cm, = 4·925 watt-seconds.

The value for the covering is derived from a direct determination of the specific heat of rubber and braiding made on a small sample taken from the cable. The actual value obtained was 0·39 calorie (= 1·63 watt-second units) per gramme per degree C., and is subject to a possible error of ± 3 per cent. The heat capacity of the covering is obtained by multiplying the value of the specific heat, given above, by the weight of the covering per unit length of cable, which weight was determined on a length of about a yard of covering.

The resistance of unit length of conductor of the 0·094-sq. in. cable at 15·6° C. was $2\cdot86 \times 10^{-6}$ ohms, and since for a current of 169 amperes maintained continuously there was a temperature-rise of 21·8 degrees C., the resistance at the higher temperature is

$$r = [1 + (0\cdot004 \times 21\cdot8)]\,2\cdot86 \times 10^{-6} = 3\cdot11 \times 10^{-6} \text{ ohm/cm}$$

Hence

$$I^2r = wM = 3\cdot11 \times 10^{-6} \times 169^2 = 8\cdot83 \times 10^{-2} \text{ watt}$$

and
$$w = \frac{8\cdot83 \times 10^{-2}}{21\cdot8} = 4\cdot06 \times 10^{-3} \text{ watt}$$

Thus the thermal time-constant

$$\gamma = c/w = 4\cdot925/(4\cdot06 \times 10^{-3}) = 1\,210 \text{ seconds.}$$

Example (2). *A lead-covered paper-insulated single* 0·1-*sq. in. cable* [*see Fig.* 2 (A)].—Only the heating curve was available. The value deduced from the slope of the plotted values of $\log_{10}[M/(M-\theta)]$ was $\gamma = 1\,270$ seconds.

For the total heat capacity of unit length of cable we have :—

(1) Conductor	..	2·14 watt-sec. units.
(2) Lead covering	..	1·59 ,, ,,
(3) Paper and oil	..	1·62 ,, ,,
Total heat capacity c =		5·35 ,, ,,

$$w = \frac{I^2r}{M} = \frac{200^2 \times 2\cdot79 \times 10^{-6}[1 + (0\cdot004 \times 30)]}{30} = 4\cdot16 \times 10^{-3} \text{ watt}$$

Therefore

$$\gamma = c/w = 5\cdot35/(4\cdot16 \times 10^{-3}) = 1\,290 \text{ seconds}$$

Here again the values for the impregnated-paper insulation were derived from a determination of the specific heat of a sample taken from a cable, the actual values being—

0·37 calorie (= 1·54 watt-second units) per gramme per degree C.

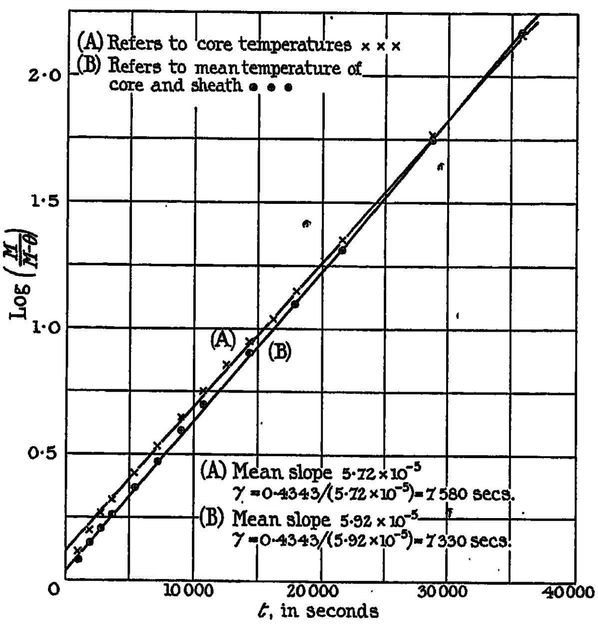

FIG. 3.—Determination of the time-constant of a high-tension three-core paper-insulated cable with lead covering and armouring.

Example (3). *A lead-covered paper-insulated concentric* 0·1-*sq. in. cable* [*see Fig.* 2 (B)].—Only the heating curve was available. The value deduced from the slope of the plotted values of $\log_{10}[M/(M-\theta)]$ was $\gamma = 2\,170$ seconds. In this case θ was the mean value of the temperature-rises of the inner and outer conductors, respectively.

For the total heat capacity of unit length of cable we have :—

(1) Conductor (inner and outer) 4·27 watt-sec. units
(2) Lead covering .. .. 2·77 ,, ,,
(3) Paper and oil .. .. 4·93 ,, ,,
Total heat capacity per cm $c = 11{\cdot}97$,, ,,

$$w = \frac{I^2r}{M} = \frac{2 \times 170^2 \times 2{\cdot}7[1 + (0{\cdot}004 \times 30{\cdot}6)]10^{-6}}{30{\cdot}6}$$
$$= 5{\cdot}72 \times 10^{-3} \text{ watt}$$

Therefore

$$\gamma = c/w = 11{\cdot}97/(5{\cdot}72 \times 10^{-3}) = 2\,100 \text{ seconds}$$

Example (4).—*A high-tension 3-core paper-insulated armoured cable on which a number of heating curves both of core and lead sheath were taken, special attention being directed to accuracy of the intermediate observations on the curve.*—In Fig. 3 are plotted the values of

TABLE 1.

Cable size (Nominal)	Thermal time-constant		Multiplying factor for rubber		Multiplying factor for paper	
	Rubber	Paper	½-hour rating	1-hour rating	½-hour rating	1-hour rating
sq. in.	secs.	secs.				
0·0145	520	700	1·02	1·00	1·05	1·00
0·0225	606	760	1·03	1·00	1·06	1·01
0·04	890	900	1·07	1·01	1·09	1·01
0·06	1 090	1 050	1·11	1·02	1·12	1·02
0·075	1 350	1 150	1·17	1·04	1·15	1·03
0·1	1 520	1 320	1·21	1·05	1·18	1·04
0·12	1 630	1 430	1·23	1·06	1·20	1·05
0·15	1 820	1 600	1·26	1·08	1·23	1·06
0·2	2 190	1 850	1·34	1·11	1·27	1·08
0·25	2 440	2 070	1·38	1·14	1·32	1·10
0·3	2 810	2 250	1·46	1·18	1·36	1·13
0·4	3 390	2 620	1·57	1·24	1·43	1·17
0·5	3 690	2 925	1·61	1·27	1·49	1·20
0·6	4 060	3 185	1·67	1·30	1·54	1·23
0·75	4 100	3 520	1·68	1·31	1·60	1·26
1·0	4 510	3 970	1·74	1·35	1·66	1·30

$\log_{10}[M/(M - \theta)]$ against time, (A) referring to the temperature of the core only, and (B) to the average temperature of core and sheath. The values of the thermal time-constant are 7 580 seconds from curve (A), and 7 330 seconds from curve (B), as against the value of 7 100 seconds deduced from the dimensions and thermal constants of the components of the cable. In calculating the heat capacity, the effect of the armouring has been ignored since it is separated from the lead sheath by tape and obviously cannot be regarded as adding appreciably to the heat capacity of the cable.

In the first example there is a difference of about 7 per cent between the two determinations, which, however, is not large when the difficulties of the various measurements are taken into account. It is, of course, possible that the difference arises from the fact that the two methods of determination apply to conditions that are not strictly comparable. The heating or cooling curve refers to a cable in contact with the floor (the effect of which is nearly equivalent to that of a wood casing or iron pipe), whereas the calculation from the dimensions and specific heats of the constituent parts of the cable leaves this factor entirely out of account.

TABLE 2.

Cable size (Nominal)	Permissible current			Size of cable that will carry same current as for continuous rating, but for:—	
	½-hour rating	1-hour rating	Continuous rating as in I.E.E. Wiring Rules	(1) ½ hour	(2) 1 hour
			Rubber cables.		
sq. in.	amps.	amps.	amps.	sq. in.	sq. in.
0·0145	38	37	37	0·0145	0·0145
0·0225	47	46	46	0·0225	0·0225
0·04	68	65	64	0·04	0·04
0·06	92	85	83	0·06	0·06
0·075	113	101	97	0·075	0·075
0·1	142	124	118	0·1	0·1
0·12	160	138	130	0·1	0·12
0·15	191	164	152	0·12	0·15
0·2	247	204	184	0·15	0·2
0·25	295	244	214	0·2	0·25
0·3	351	283	240	0·2	0·25
0·4	452	357	288	0·25	0·3
0·5	534	422	332	0·3	0·4
0·6	641	499	384	0·4	0·5
0·75	774	604	461	0·5	0·6
1·0	1 036	803	595	0·6	0·75
			Paper cables.		
0·0145	60	57	57	0·0145	0·0145
0·0225	79	75	75	0·0225	0·0225
0·04	113	105	104	0·04	0·04
0·06	151	138	135	0·06	0·06
0·075	180	162	157	0·075	0·075
0·1	225	199	191	0·1	0·1
0·12	252	220	210	0·1	0·12
0·15	303	261	246	0·12	0·15
0·2	376	320	296	0·15	0·2
0·25	453	377	343	0·2	0·25
0·3	523	435	385	0·25	0·3
0·4	663	543	464	0·3	0·4
0·5	804	648	540	0·4	0·5
0·6	960	767	624	0·4	0·5
0·75	1 180	930	738	0·5	0·6
1·0	1 548	1 211	932	0·6	0·75

The following examples will serve to show the effect on the rating factor of an uncertainty of this order in the evaluation of the thermal time-constant. Taking the formula for the calculation of the rating factor in the case already quoted (page 364), i.e. a cable which runs for 4 minutes at full load and 6 minutes at half load, it was found that if the thermal time-constant were taken as 1 300 seconds the "full" current could be increased to 1·304 times the normal current for continuous rating. If instead of 1 300 seconds the thermal time-constant were here taken as 1 200 seconds then the value obtained for the rating factor would be

$$n = 2\sqrt{\left[\frac{(1-e^{-600/1\,200})}{4(1-e^{-240/1\,200}) + (1-e^{-360/1\,200})e^{-240/1\,200}}\right]}$$

$$= 2\sqrt{\left[\frac{0\cdot3935}{(4\times0\cdot1813)+(0\cdot2593\times0\cdot8187)}\right]} = 1\cdot295$$

a difference of less than 1 per cent.

Take next the formula for the ½-hour rating

$$n = \frac{1}{\sqrt{(1-e^{-T/\gamma})}}$$

where T the working period is ½ hour (= 1 800 secs.).

If $\gamma = 1\,200$,

$$n = \frac{1}{\sqrt{(1-e^{-1\,800/1\,200})}} = \frac{1}{\sqrt{(1-0\cdot2231)}} = 1\cdot134$$

But if we take $\gamma = 1\,300$

$$n = 1/\sqrt{(1-e^{-1\,800/1\,300})} = 1/\sqrt{(1-0\cdot2503)} = 1\cdot155$$

a difference of 1·9 per cent for a variation of 8 per cent in the thermal time-constant.

Table 1 gives the time-constants and the direct multiplying factor both for ½-hour and 1-hour rating for low-tension cables of sizes and dimensions as shown in the I.E.E. Wiring Rules, and Table 2 gives the actual permissible currents for this type of rating, and the sizes of cables which may be used for ratings of ½ hour and 1 hour in place of the sizes at present specified in the Wiring Rules for continuous loading.

The thanks of the authors are due to Mr. S. Butterworth for his kindness in checking the mathematical portions of the work, and to Dr. Ezer Griffiths who determined the values of the heat capacity of the dielectric covering materials.

AMERICAN PRACTICE AS REGARDS THE GENERATION OF SUITABLE VOLTAGES AND CURRENTS FOR DEEP THERAPY.*

By C. H. HOLBEACH, Associate Member.

(*Paper first received* 31*st March, and in final form* 6*th November,* 1922.)

SUMMARY.

In the past few years considerable strides have been made in the improvement and simplification of X-ray equipment both for medical and industrial purposes. At the same time it is a noteworthy fact that the demands of X-ray workers are ever in advance of the apparatus at their disposal. It is for this reason that standardization is difficult, a design becoming almost obsolete as soon as perfection is approached.

The comparatively sudden call for highly penetrative X-radiations of shorter wave-length, involving the maintenance of 200 000 volts at the tube terminals for continuous running, has imposed many difficult problems on the designer and manufacturer. In America these difficulties were to a great extent solved by research laboratories of large electrical corporations. The influence of sound engineering principles is, therefore, more noticeable in American practice than in that of any other country.

INTRODUCTION.

A certain ambiguity might be attached to the title of this paper, inasmuch as it presupposes the existence of a "practice" relative to the generation of high voltages for deep therapy in the United States. As only a short time has elapsed since medical authorities definitely called for shorter wave-length X-radiations, it might be argued that such an assumption is unduly hasty.

After careful consideration of the material and data available one might safely assert that a distinct practice exists. There is ample evidence of a fundamental similarity in equipment of apparatus placed at the disposal of American doctors for the treatment of deep-rooted malignancy. Such a condition of things, absent in the majority of other countries, is perhaps governed by circumstances peculiar to the United States.

In a general way one might perhaps suggest that the object of this paper is to point out some tentative lines along which a practice might be evolved in this country. There can be very little doubt of the ultimate benefit which would accrue from the standardization of electro-medical apparatus. At the present time there is a lamentable state of affairs which finds no parallel in other departments of electrical engineering. The medical man is faced with a host of conflicting recommendations which make his task an unnecessarily difficult one. There is no reason why a definite conclusion should not be arrived at, once and for all, to decide upon the basic principles which are to underlie the design of apparatus for deep therapy. Special refinements and secondary matters can be left to the discretion, enterprise and individuality of the manufacturer.

It is within the scope of this paper, therefore, to point out the steps taken by American manufacturers in perfecting their equipment, and it should be clearly understood that criticism will be excluded as far as possible, unless it is particularly required in order to emphasize some important point. Also, comparisons with similar efforts in this country will not be attempted, and indeed should be avoided, in view of the totally different conditions, both economic and otherwise, which, unfortunately, bind engineers in both countries.

FUNDAMENTAL PRINCIPLES OF AMERICAN DESIGN.

The problems in the generation of high voltages for deep therapy are mainly centred upon:—

(1) The type and form of the high-voltage generator.
(2) The choice of X-ray tube to withstand 200 000 volts and over.

It is interesting to note that it is upon these more important general principles that, without exception, all manufacturers in the United States are in entire agreement. In order, therefore, to provide a means of generation of the higher order of potentials, recourse has been made to the a.c. oil-immersed transformer. The reasons are many, and certain external influences have, without doubt, had a measured bearing on this universally accepted principle. The presence, for instance, of alternating current in larger areas in the United States is in all probability a strong factor in this case. High-voltage electrical engineering has been applied to a far greater extent in America than in any other country. It is, therefore, scarcely surprising that manufacturers of X-ray apparatus should turn to a precedent which is already established in industrial circles. Transformers to operate on 200 000 volts were constructed some years ago in connection with high-voltage transmission lines in California and elsewhere.

Moreover, a transformer has been constructed having a secondary ratio up to 1 000 000 volts. An impression seems to be current in X-ray circles in this country that this apparatus was built by Dr. Coolidge for X-ray purposes. A correction is necessary, as the transformer in question was designed and assembled at the Pittsfield laboratories for the investigation of problems in connection with high-tension transmission lines.

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e.g. corona losses, lightning flash-over, and insulation tests.

But the main consideration regarding the adoption of a transformer in preference to a coil equipment is a purely electrical one, in the sense that engineers and research physicists have shown a marked preference for the former for continuous working with a minimum of attention.

The design of the X-ray transformer roughly coincides with its industrial prototype, inasmuch as without exception the core-type construction is used, with concentric windings and circular coils. In all instances the practice of oil immersion is followed for obvious electrical reasons. Experiments have been conducted at the Research Laboratory of the General Electric Co. at Schenectady, with a view to making a direct comparison of the X-ray intensities obtained from a Coolidge tube operated both on an induction coil and on an interrupterless transformer outfit. The measurements were made at 1 milliampere and 296 000 volts peak. The intensity was measured with various filter thicknesses of copper by means of a specially constructed ionization chamber. The results are given in the following table.

Induction coil. 1 mA at 296 kV (max.)			Experimental interrupterless machine 1 mA at 296 kV (max.)		
Thickness of copper	Time, T	Intensity, $(1/T) \times 10^3$	Thickness of copper	Time, T	Intensity, $(1/T) \times 10^3$
mm	secs.		mm	secs.	
0·1	9·1	109·9	0·1	9·1	110·0
0·2	10·8	90·0	0·2	11·3	88·6
0·3	12·9	77·5	0·3	13·2	75·8
0·5	15·7	63·8	0·5	16·9	59·2
0·7	18·2	55·0	0·7	18·1	55·3
1·0	22·2	45·1	1·0	22·6	44·3
1·5	29·6	33·8	1·5	29·3	34·1

The curve showing the relationship between intensity and filter thicknesses is shown in Fig. 1. It will be

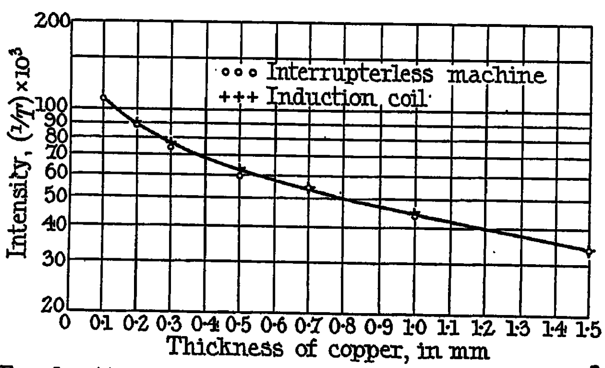

FIG. 1.—Absorption curves of interrupterless machine and induction coil; 296 kV (max.), 1 mA.

noted that all the points lie roughly on one line, and it is therefore obvious that any differences, both quantitative and qualitative, are such as may be assigned to experimental error. It is also evident that the virtues claimed for the induction coil are of no special value in relation to their operation with a hot-cathode tube, whereas, on the other hand, we have the manifold disadvantages of coil construction and the inconsistency in the running and upkeep of mercury interrupters.

HIGH-VOLTAGE TUBES.

The only type of tube employed by American manufacturers is the new high-voltage deep-therapy Coolidge tube, the outcome of five or six years of experience gained in experimental work. In fact, as long ago as 1915 a tube had been constructed by Dr. Coolidge to operate on 200 000 volts and over. The present tube (see Fig. 2) is of similar design to the well-known standard, universal-type tube, and consists of a solid tungsten anode supported by the usual molybdenum stem. The overall length has been increased to 32 in. and the bulb diameter to 8 in., and the distance between

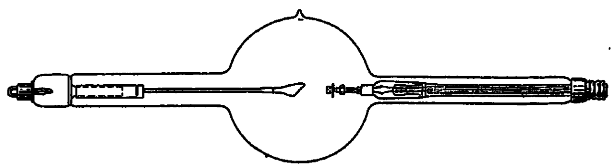

FIG. 2.

the cathode and anode has been carefully adjusted to comply with higher electrostatic strains consequent upon the increased tension. This correction minimizes the electrostatic pull on the filament, and also decreases the possibility of thermionic emission from the edges of the focusing cup. The new tube may be operated continuously at a current varying from 2 mA to 8 mA (depending entirely on the condition of the energizing supply and the methods of cooling employed). The factors limiting the energy input are governed by the volatilizing point of the tungsten anode and the melting point of glass. In the United States air-blast cooling is adopted but generally found to be unnecessary, as fully 8 mA can be passed without injury to the tube.

The current value employed determines to a great extent the ultimate life of the tube, which between 2 and 4 mA averages around 500 hours and over. Still higher currents decrease the life enormously until at 8 mA 40 hours would be considered a reasonable figure.

RECTIFICATION.

The question of the supply of direct current to the tube has been solved by the universal method of cross-arm rectification, either of the "Snook" or the 2-arm pattern, of which the disc type is a modification. These methods are well known and need no description. The experimental apparatus used by Dr. Coolidge was equipped with a rectifying switch of the "Snook" pattern, and the shaft ($12\frac{1}{2}$ ft. long) was built up of paper-shellac tubing. The four metallic cross-arms were $35\frac{1}{2}$ in. long, spaced 33 in. apart. In this apparatus rectification up to 300 000 volts was obtained without difficulty.

Although the benefits of minimizing the corona

discharge by the use of tubing instead of wire in the high-tension circuit, and carefully avoiding sharp corners, are well known, it is amazing how little this principle has been applied in this country. Its application in America has spread not only to the overhead system but also to the rectifier itself.

In Dr. Coolidge's apparatus the rotating collectors were shaped of 3-in. tubing, approximately 12 in. in length, and were fitted with hemispherical ends. The International X-ray Corporation of New York have gone a step further, and are responsible for an enterprising innovation in which the whole of the rectifying scheme involves the qualities of the sphere gap. It is claimed that by making all these collectors,

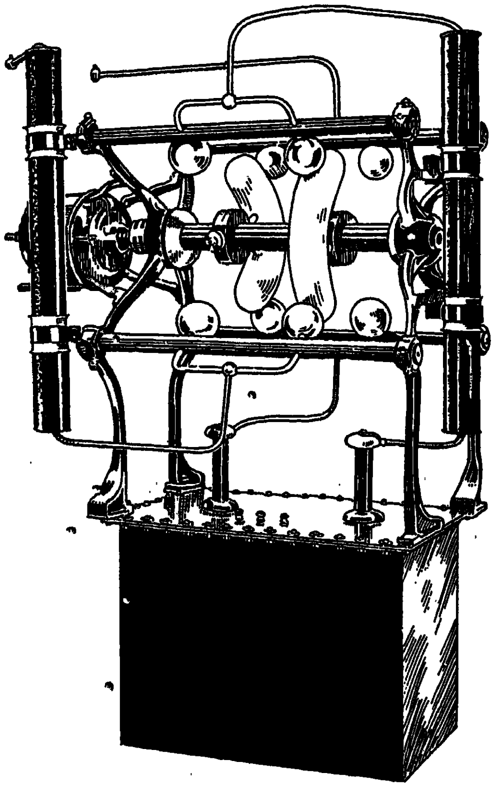

FIG. 3.

both stationary and moving, of spheres and spherical toroids, a considerable number of inconsistencies in operation would be swept away. Fig. 3 shows the "Precision" rectifier mounted in position over an oil-immersed transformer. One of the outstanding advantages of the above arrangement lies in the fact that the whole system can be made more compact, and a greater latitude in the adjustment of the rectification can apparently be obtained, in view of the considerably shorter spark-over existent between spherical electrodes. The revolving toroids are within $\frac{1}{16}$ in. of the spheres, and during operation the arcing is claimed to be very small and to take the form of short local sparks, without the usual troublesome brush discharge attendant upon other forms of rectifier.

CONSTANT-POTENTIAL APPARATUS.

Progress has been made with the methods of generating constant-potential direct currents involving the use of "Kenotron" valves. The system was first suggested and perfected by Dr. A. W. Hull of Schenectady for his work in connection with the X-ray spectrum examination of materials. The principles of the system depend, briefly, upon rectifying a high-voltage alternating current of 2 000 frequency by means of a battery of "Kenotron" hot-cathode valves. The pulsating

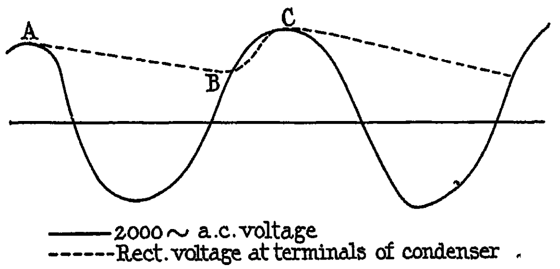

FIG. 4.

direct current is then caused to charge up condensers of a predetermined capacity. The function of these capacities is to hold their charge until the next impulse occurs. This has the effect of flattening out the wave-shape, as shown in Fig. 4. In this manner a high potential is delivered to the X-ray tube, with a deviation of less than 1 per cent.

It is impossible to do full justice to this system in view of the many intricate factors which it would be necessary to discuss. Recently, however, an apparatus of this description has been designed and operated at a voltage of 200 000. The arrangement of connections

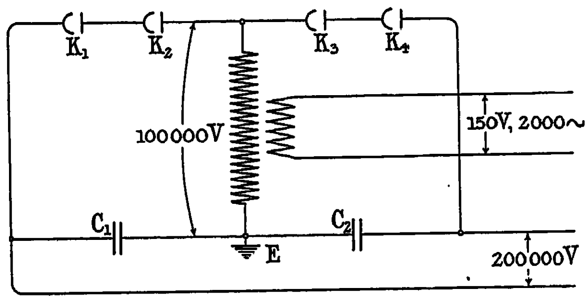

FIG. 5.

is shown in Fig. 5. The supply to the primary of the transformer is obtained from a dynamometer-type generator giving 2 000 periods at 150 volts. The transformer itself sustains 100 000 volts at its secondary terminals, and is fed alternatively through the Kenotron valves K_1, K_2, K_3 and K_4, to the condensers C_1 and C_2. The tube is connected to the outer terminals of C_1 and C_2. A very fine adjustment of the secondary voltage is obtained by controlling the capacities of the condensers. In order to equalize the capacity currents, a small variable condenser is shunted across each valve. In this manner an even distribution of the voltage strains is obtained. At the present time no "Kenotron" valves have been constructed to operate at pressures above 150 kV, but no particular difficulty is anticipated in

their development up to 200 000 volts if occasion demands. As soon as these higher power " Kenotron " valves are in use one valve may be substituted for the two, placed in each circuit as shown in the figure. The transformer is of very moderate dimensions, weighs only 85 lb. and has an open core. At the present time the transformer has been designed for 100 000 volts, but the voltage can readily be increased to 200 000 thus giving without any difficulty a constant potential of 300 000 volts at the terminals of a Coolidge tube. A comparison between the relative X-ray output of constant-potential apparatus, and of an a.c. transformer

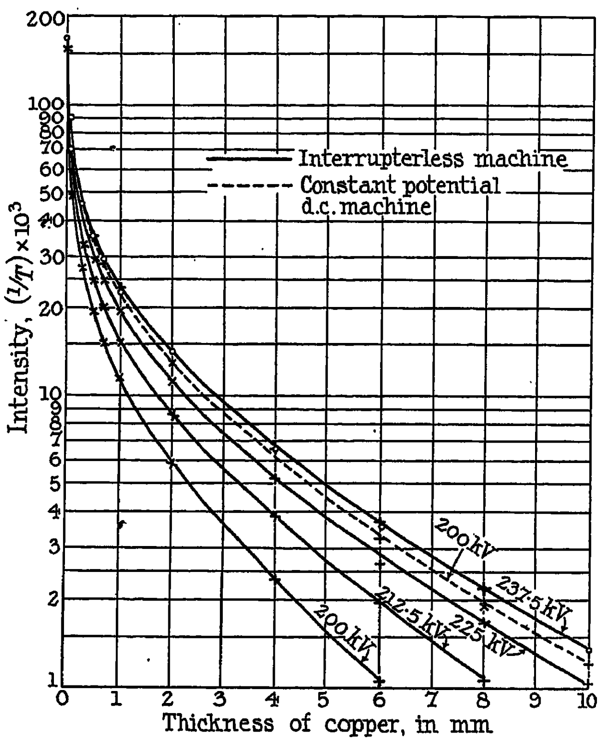

FIG. 6.—Absorption curves.

with mechanical rectifier, indicates a distinct margin in favour of the former. Fig. 6 shows this relationship clearly. To obtain the same X-ray intensity under identically similar conditions, 225 kV is required from an a.c. transformer outfit, as against 200 kV for the constant-potential apparatus. These comparative tests form a part of an extensive series of quantitative research problems which have been investigated by Dr. Coolidge and W. K. Kearsley at the Schenectady laboratory. The results have recently been published by *The American Journal of Roentgenology*. In summarizing the last-mentioned test Dr. Coolidge states that the difference might be due either to experimental inaccuracy or to the fact that the composition of the beam of X-rays is not exactly the same in both cases.

RESEARCH.

Although research on this very important subject is not entirely confined to the " Victor " and the General Electric Co.'s combination, one necessarily feels that the most authoritative statements emanate from the Schenectady laboratories. Dr. Coolidge a year or so ago made a special journey to the Continent to study the question of deep-therapy equipment. Since then the research staff under his direction have had the opportunity of closely investigating the relative values of the most important types of German deep-therapy apparatus. Research of a very thorough and exhaustive nature has been carried out and recently published. In this way the benefits of unique experience are passed on to all concerned. The material outcome of this work is centred upon the deep-therapy outfit produced by the Victor X-ray Corporation at Chicago, a brief description of which will be given later in the paper. A summary of the already pub-

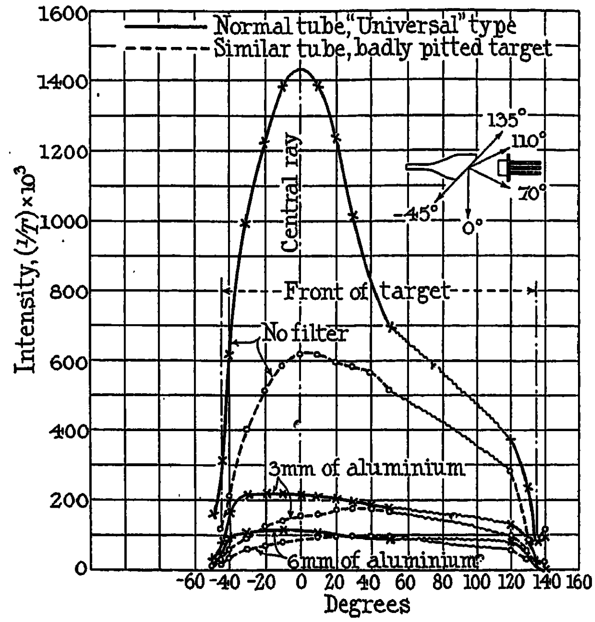

FIG. 7.—Distribution in plane containing tube axis and perpendicular to target face; 127 000-volt, 3-mA interrupterless machine.

lished research work would indicate the following conclusions :—

(1) The oil-immersed a.c. transformer, in conjunction with a mechanical rectifier and the constant-potential machine, is the most efficient means of generating high voltages for continuous working.
(2) The present-day form of mechanical cross-arm type rectifier lends itself admirably, if suitably modified, to the rectification of higher potentials.
(3) The ballasting action of resistance offers certain well-defined advantages over auto-transformer control when operated with a hot-cathode tube at high potentials.
(4) A voltmeter connected across the primary of an a.c. transformer should be calibrated against a standard sphere gap.
(5) The current in the secondary or tube circuit must be kept virtually constant in order to minimize the high-tension voltage fluctuations due to the resistance in the primary circuit.

With regard to Coolidge tubes for deep therapy, experimental data are now available, the most important of which are as follows :—

(1) The 200 000-volt tubes have a substantially constant output. The filtered radiations through 2 mm of copper varied only $1\frac{1}{4}$ per cent over a series of 29 tubes, the terminal voltage being 200 kV at 2 mA.
(2) Where no filter is used for superficial skin therapy this constancy is lessened, owing to a slight variation in the thickness of the tube wall.
(3) The effect of the tungsten deposit on the inner walls of badly abused tubes may be neglected in deep therapy.

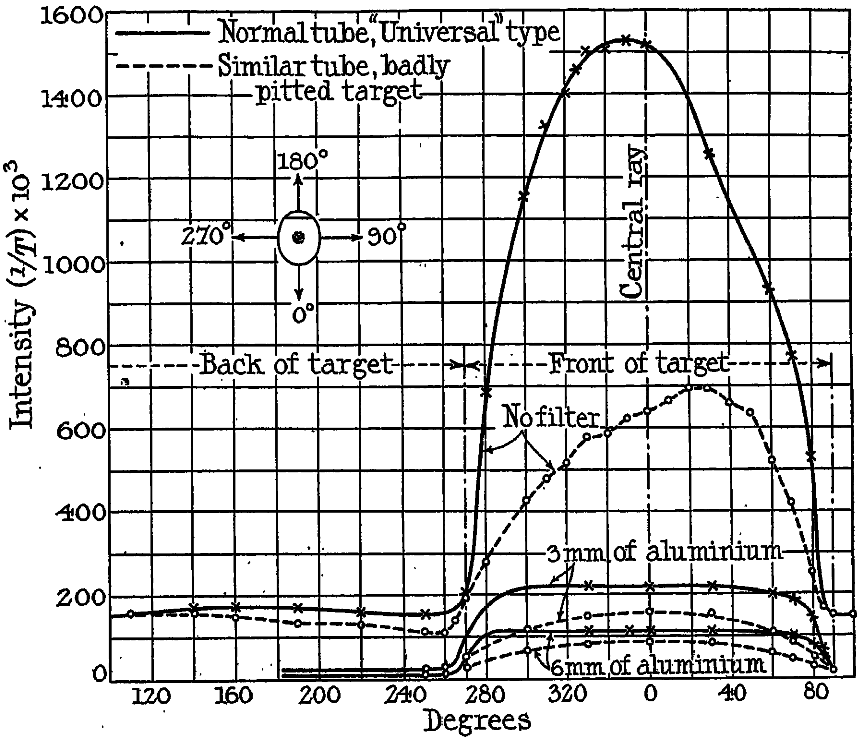

FIG. 8.—Distribution about girdle of tube; 127 000-volt (max.), 3-mA interupterless machine.

(4) The distribution of intensity around the girdle, and in a plane containing the tube axis and perpendicular to the target face, varies markedly and, therefore, the angle at which the tube is operated is a factor of sufficient importance to warrant close attention. Figs. 7 and 8 illustrate the distribution in a quantitative manner.

The angles necessary for the application of X-rays through various ports of entry are in the latter case obtained by tilting a tubular or conical diaphragm placed in the path of, and radial to, the central beam. The radiations of varying incident angle are therefore directed on to the patient. It is obvious from the data already given that this technique must be carefully adjusted in order to allow for varying X-ray distribution from the focal spot. At the same time it should be noted that for filtered radiations the distribution is greatly flattened. Within the girdle of the tube the distribution is constant within angles of 100°.

These results are of the utmost importance in view of the fact that some workers in this country either have installed or are contemplating the installation of a tube carrier which is a fixture in relation to the patient.

General Design of Apparatus.

Individual manufacturers in the United States have shown considerable enterprise in perfecting and modifying existent practice in order to cope with the new conditions. Many exceptional refinements have been applied to standard plants.

It was pointed out earlier in the paper that a similarity of design is noticeable. It would therefore be both superfluous and beyond the scope of this paper to give a detailed description of each piece of apparatus on the market, but it might be of interest to describe briefly some of the outstanding features of the more important American models.

A point worthy of note is that the twin-coil practice common in Germany has been followed in a modified form by some American manufacturers, and both the Waite and Bartlett Manufacturing Co. and the Wappler Electric Co. of New York have designed their transformer equipment in two halves. The latter company have two separate transformers energized in parallel,

each being capable of transforming the line pressure to 150 000 volts. The transformers are oil-immersed and consist of concentric, heavily insulated, primary and secondary coils. Two tubes may be operated simultaneously, each taking alternate half-waves or, if desired, both halves can be applied unidirectionally to the tube. The diagram of connections is given in Fig. 9. Special importance is claimed for the inclusion of suitably designed ohmic resistances in the secondary circuit. Impressed surges and oscillations are minimized, the tube thereby safeguarded, and quite uniform running is maintained. The two rotating disc rectifiers are mounted centrally within the usual cabinet, over and above two oil-immersed high-tension transformers. Large ebonite shields are mounted at the stator to obviate the chances of flash-over to the earthed portion current, time, and filter thickness. Dr. Waite attributes the utmost importance to this device, which eliminates carelessness on the part of the operator and, moreover, provides a permanent record of each treatment.

Mention has already been made of the rectifying system evolved by the International X-ray Co. of New York. Another interesting feature of the outfit consists of a new method of measuring the secondary voltage or penetration. This is done by detecting and calibrating the capacity current of a specially designed, concentric, air-dielectric condenser. The latter is mounted on the top of a cabinet, and a galvanometer or milliammeter is employed to record the capacity or corona current between the plates, the readings being directly calibrated in peak volts. The general appearance of the X-ray transformer and rectifier apparatus has

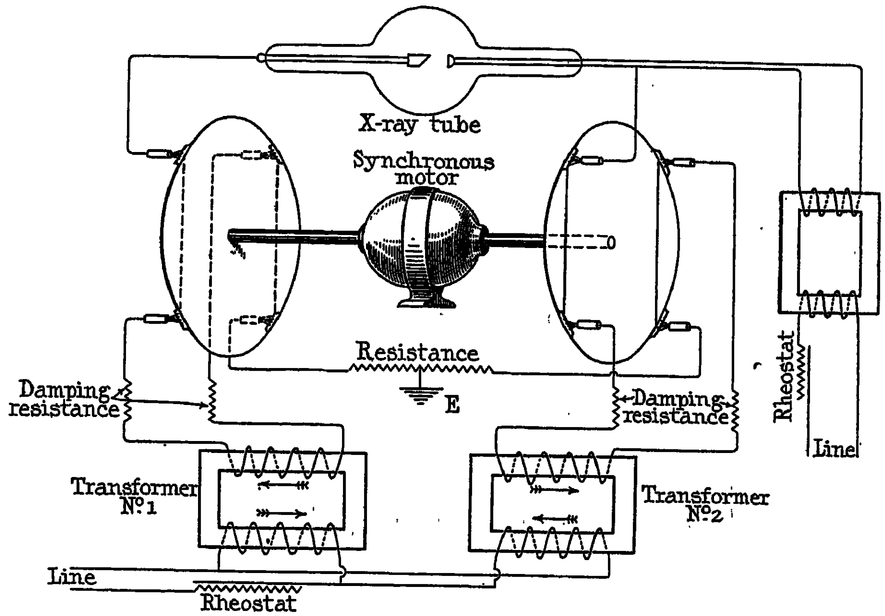

FIG. 9.—Diagram of connections of Wappler deep-therapy machine

of the mountings, for instance the synchronous driving motor. The new high-voltage Coolidge tube is used and mounted in an ingenious protective container completely enclosed in such a way as to allow a draught of cold air projected by a fan to circulate around the tube bulb and out at the two arms. A sphere gap and coronaless overhead equipment is included in the installation.

The Waite and Bartlett machine is somewhat of the same construction and has a single motor driving a shaft with a rectifier operating on the 4 cross-arm principle. The currents when rectified are put in series and fed to the tube terminals. A sphere gap and a primary a.c. voltmeter are included for measuring and standardizing the voltage. A machine of this type has been installed at the General Memorial Hospital under the direction of Professor Shearer, of Cornell University, who has devised a special recording instrument by means of which an ink record is taken of fluctuations (if any) in the primary voltage, the secondary already been illustrated in Fig. 3. The device is mounted on the top of the cabinet, and consists of a condenser, the discharge between the plates of which is measured through a galvanometer or milliammeter calibrated directly in peak volts.

It is claimed that by this means the errors due to the unskilled manipulation of a sphere gap are eliminated. Controls are obtained by a ballast resistance in the primary circuit of an oil-immersed transformer.

The actual design of transformer presents some interesting features. The secondary coils are completely suspended in oil, and no solid insulation or filling compound is used. The high-tension turns are made up of specially insulated wire capable of withstanding 5 000 volts (between turns). The transformer was designed by Mr. Montford Morrison and has proved to be exceptionally free from breakdown.

A powerful apparatus is manufactured by the Victor X-ray Corporation of Chicago, and is the practical outcome of the experience of their engineers in collabora-

tion with the research work of Dr. Coolidge and his staff at the General Electric laboratories, Schenectady. Essentially the plant consists of a transformer capable of operating continuously at 280 000 volts, equivalent to a 20-in. gap between points. Rectification is obtained by the well-known Snook pattern cross-arm rotating switch. Special provision has been made to eliminate harmful surges. The apparatus has been designed with a view to its use on a still higher peak voltage than has so far been considered necessary for deep-therapy treatment. For this reason a greater latitude is allowed in the dimensions of the rotating switch, which is 5 to 6 ft. long and occupies the whole length of the cabinet. The cabinet, as usual, encloses the transformer and rectifying switch. The rotary switch is placed horizontally the whole length inside the cabinet. Noteworthy features of the apparatus are the inclusion of a Kearsley stabilizer, double-check milliammeters, and a conveniently placed sphere-gap voltmeter. The current stabilizer operating on the same principle as the Tirrill regulator is all-important, as it keeps the current virtually constant, even if considerable fluctuations occur in the line voltages. The results of the researches at Schenectady have proved the advisability of introducing two milliammeters in the tube circuit. It was found that surges which, although minimized, are unavoidable have been known to cause a partial short-circuit in the shunted resistance across the moving coil. A carefully calibrated meter of standard type was found to have failed in this manner after a very short period of use, and it was considered extremely improbable that two meters should fail in a similar manner at the same time. The voltages are measured by a voltmeter placed in the primary circuit of the transformer and calibrated against the sphere gap. Special attention has been given to the overhead system, which is made up of ¾-in. tubing and is so designed as to obviate all corona and attendant dangers. The output of the machine is as high as 8 mA at 200 kV and has an equivalence of 50 mg of radium. As many as 45 of these outfits are in use and are giving very satisfactory and consistent results.

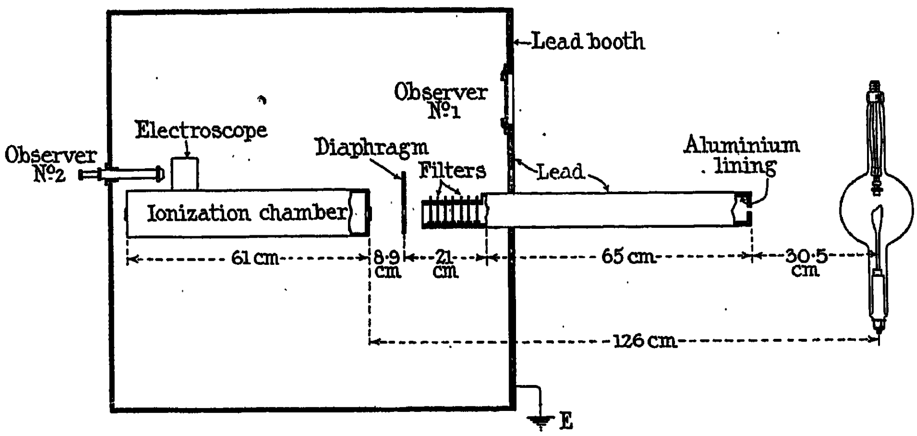

FIG. 10.

FUTURE DEVELOPMENTS.

It would appear that the limiting factors at the present time rest with the X-ray tube, and hence future developments depend entirely on the production of higher-power Coolidge tubes before apparatus for the generation of still shorter wave-lengths can be manufactured.

With regard to the question of standardizing methods of measurement for X-radiation, it appears that authorities in the United States do not recommend the use of an ionization chamber in everyday work. In the laboratory, of course, this method is pre-eminent, but, owing to the many disturbing factors requiring highly skilled manipulation, average accuracy could better be obtained by the use of a sphere gap checked by a primary a.c. voltmeter and double-check milliammeters. Still further accuracy would be obtained by the inclusion of some form of current stabilizer in the tube circuit. Differences in wave-shape may be neglected, as the quality and intensity of X-rays produced thereby are little altered, if the radiation is standardized in the first place for the maximum peak voltage.

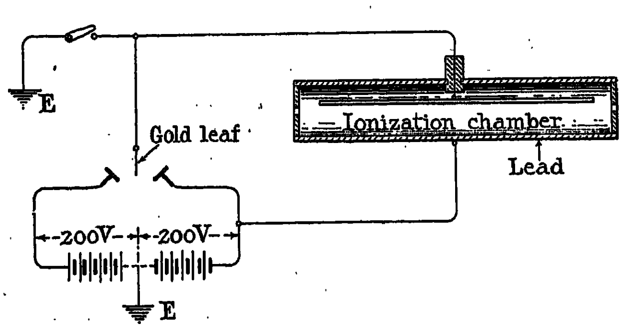

FIG. 11.

All sphere-gap measurements are performed in accordance with the recommendations and specifications issued by the Bureau of Standards of the American

Institute of Electrical Engineers, a very well-considered publication which is always a point of reference with regard to the measurement of the higher order of voltages.

Measurements in the laboratory by Dr. Coolidge were accomplished by means of the ionization apparatus shown in Fig. 10. The chamber itself is enclosed within a lead booth $\frac{1}{4}$ in. in thickness facing the tube, and $\frac{3}{16}$ in. elsewhere. It is found necessary, in order to protect the chamber from X-rays, to keep the door at the back closed throughout the measurement.

Fig. 11 illustrates the detailed arrangement of an ionization chamber connected with a dry battery and Bumstead electroscope.

In conclusion, the author would like to acknowledge the assistance and courtesy accorded to him by X-ray manufacturers in the United States. Also, special acknowledgment is due to Dr. W. D. Coolidge of the General Electric Co. Research Laboratory of Schenectady and to Dr. H. M. Imboden, the editor of *The American Journal of Roentgenology*, for permission to use the extract of Dr. Coolidge's paper before publication.

AN APPARATUS FOR DEMONSTRATING THE MAGNETOMOTIVE FORCES PRODUCED BY SINGLE-PHASE AND POLYPHASE WINDINGS.*

By R. D. ARCHIBALD, Member.

(*Paper first received* 21*st July, and in final form* 16*th November*, 1922.)

SUMMARY.

A description is given of a simple method of showing the variation in the M.M.F. of a single-phase alternator winding by the shadow of a vane attached to a rotating spindle.

The application of the same principle to the case of polyphase windings, and the method of arriving at the position and dimensions of the vanes, are explained.

An apparatus is described which is arranged to show the M.M.F. produced in the air-gap of an induction motor by the stator and rotor windings under load conditions, with the rotor either stalled or revolving.

The apparatus described was devised some years ago by the author for the purpose of demonstrating the rotating fields of induction motors and other a.c. machines. Since then it has been improved upon, and it is thought that a description of it might be of interest.

The principle on which it depends can be readily understood from the case of a single-phase winding with one slot per pole per phase (see Fig. 1). If the currents in the windings vary according to a sine law, the amplitude, a, of the M.M.F. curve varies in simple harmonic motion from a positive to a negative maximum. These variations can be shown on a screen by the shadows of vanes attached to a spindle rotated at a uniform speed, the beam of light being parallel and directed at right angles to the spindle, as shown in Fig. 2. The radial lengths of the vanes are equal to the maximum value of the M.M.F. The width of the conductor has been neglected in Figs. 1 and 2, so that the M.M.F. curve is a rectangle. We shall continue for the present to neglect the spaces occupied by the conductors in the slots, as these can easily be taken into account later.

With several slots per pole per phase the M.M.F. curve is stepped as shown in Fig. 3, in which there are three slots per pole per phase, and the vanes have to be shaped accordingly.

In the case of polyphase windings with one slot per pole per phase the vanes must have a width equal to the distance between the coil side of one phase and that of the adjacent phase. The radial length of the vanes must be equivalent to the maximum value of the resultant M.M.F. over the part of the armature periphery to which they correspond. The principle of construction is shown in Fig. 4 for the case of a two-phase winding. The vanes representing the M.M.F.'s of each phase are shown unshaded at I, I′ (corresponding to phase I) and at II, II′ (corresponding to phase II). The vanes representing the resultant M.M.F.'s at various positions round the armature periphery (or along the spindle) are shown shaded. They are the resultants of the unshaded vanes at any point along the spindle and are used for projecting the M.M.F. curve produced by the two phases. The unshaded vanes are, of course omitted, being mentioned here only for the sake of explanation.

The exact dimensions and positions of the resultant vanes may be determined as follows:—

Let a be the maximum M.M.F. produced by each phase—i.e. the radial length of an unshaded vane. Consider the first shaded vane at the left-hand end of the spindle. It is the resultant of vanes I and II′ at right angles to one another and it will therefore have

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a radial length of $a\sqrt{2}$, and be at an angle of 45° to I and II′. If we measure the angular position of the vanes around the spindle in an anti-clockwise direction starting from the position of vane I, the angular position of the resultant vane can be defined as -45. This is a time angle. Distances along the spindle represent space angles or electrical degrees of armature periphery. The width of the vane expressed as a space angle is 90 electrical degrees. The positions, widths and radial lengths of the vanes can be tabulated as shown in Table 1.

If there are several slots per pole per phase the M.M.F. changes at each slot, and separate vanes are required for each pair of adjacent slots, i.e. there are as many vanes as there are teeth.

positions of the vanes which would project these M.M.F. curves are shown by the vectors to the right of the diagrams.

The total M.M.F. due to all three phases is plotted in Fig. 6. The vector diagrams below the total M.M.F. curve show how the radial lengths and positions of the resultant vanes are found from those due to each phase. For example, vane a is the resultant of vanes I, II and III at the position marked a on the total M.M.F. curve. Each vane has a width equal to a slot pitch (since the slot width is neglected), or 20 electrical degrees.

The horizontal and vertical components of the vanes of each phase and resultant vanes and their angular positions are given in Table 2.

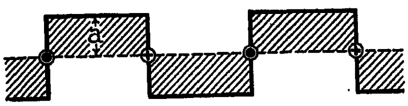


FIG. 1.

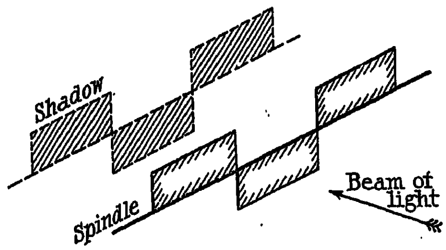


FIG. 2.

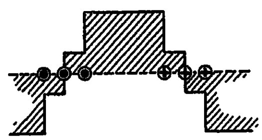


FIG. 3.

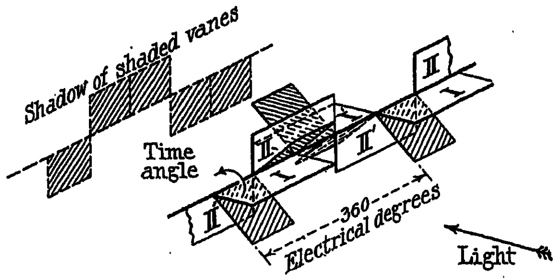


FIG. 4.

In order to show how the positions and dimensions of the vanes for a polyphase winding with several slots per pole per phase may be worked out on the above lines, an example of a three-phase winding with three slots per pole per phase is given in Fig. 5. The M.M.F.'s produced by each phase are shown at I I′, III III′, II II′. The current, and therefore the M.M.F. in phase III, is a maximum, so that the currents in phases I and II are half the maximum. The angular

TABLE 1.

No. of vane (starting from left)	Radial length	Width, in electrical degrees	Angular position around spindle
1	$a\sqrt{2}$	0–90	-45
2	$a\sqrt{2}$	90–180	45
3	$a\sqrt{2}$	180–270	135
4	$a\sqrt{2}$	270–360	225

When the resultant vanes are mounted on the spindle over a space angle of 360 electrical degrees their projections in a direction parallel to the axis of the spindle appear as shown in Fig. 7. The ends of the projections of the vanes are on the hexagon (shown dotted). It is as important to have the projection of the vanes in an axial direction as it is to have it at right angles to the spindle, for the diagram so obtained gives a clear insight into the character of the winding. Each radial vector in Fig. 7 represents in phase and magnitude the M.M.F. opposite a tooth or space, with the corresponding letter in Fig. 5. The difference of M.M.F. between any one tooth and the next is caused by the ampere-conductors in the intervening slot; but the difference between any two M.M.F. vectors such as a and b (see Fig. 7) is the line joining a and b. Such lines as ab, bc, etc., therefore represent in phase and magnitude the ampere-conductors per slot between a and b, b and c, etc. These distances should all be equal in this case, since the number of conductors per slot and the maximum current in each is the same, and if the vanes have been properly calculated by the preceding method it

will be found that the ends of the vectors in Fig. 7 divide the hexagon into two equal parts.

It will now be seen that we can arrive at the positions of the vanes more readily from this diagram than by the preceding method, by drawing the vectors of ampere-conductors per slot so that they are added together and form a closed polygon in 360 degrees. Radii are then drawn from the centre to the junctions of these vectors, thus giving the required positions of the vanes.

With symmetrical, full-pitch windings the figures bounding the vanes are simple, e.g. a hexagon for a three-phase winding, a square for a two-phase winding, and a $2n$-sided figure for n phases. With short-corded windings the shapes of the figures are slightly modified and with variable-pole windings differ considerably from the simple forms. A number of M.M.F. diagrams constructed on this principle for such windings are given in an article by W. Stiel in the *Schweizerischer Elektrotechnischer Verein Bulletin* for January, 1922.

An example of this method of construction is given in Figs. 8, 9 and 10, which show a three-phase winding with three slots per pole per phase short-corded by one slot. The current vectors are shown in Fig. 9, and the M.M.F. diagrams in Fig. 11. The M.M.F.'s at a, b, c, etc., in Fig. 8, are shown by the vectors oa, ob, oc, etc., in Fig. 11. If we call the maximum current in any one conductor 1 ampere then the ampere-conductors in the slot between a and b (Fig. 8) are two, since each conductor is carrying a current given by the vector III′ in Fig. 9. Let 1 cm = 1 ampere-conductor. The line ab (Fig. 11) is therefore drawn vertically upwards and of length 2 cm. The slot between b and c contains one conductor carrying the current given by the vector II in Fig. 9, and one carrying current given by the vector III′. The length bc is therefore the resultant of a distance of 1 cm drawn in phase with the vector II, and 1 cm drawn in phase with the vector III′. Similarly, cd is 2 cm drawn in phase with the vector II, and so on.

In order to show the more correct trapezia form of M.M.F. curve it is only necessary to narrow down the vanes to the width of a tooth and join the outer corners of the adjacent vanes by a straight thread or wire. The outer edges of the vanes then trace out the M.M.F.'s over the teeth, and the threads or wires trace the M.M.F.'s over the slots. The idea will be gathered from Fig. 10, which shows three vanes connected in this way and the shadows produced thereby.

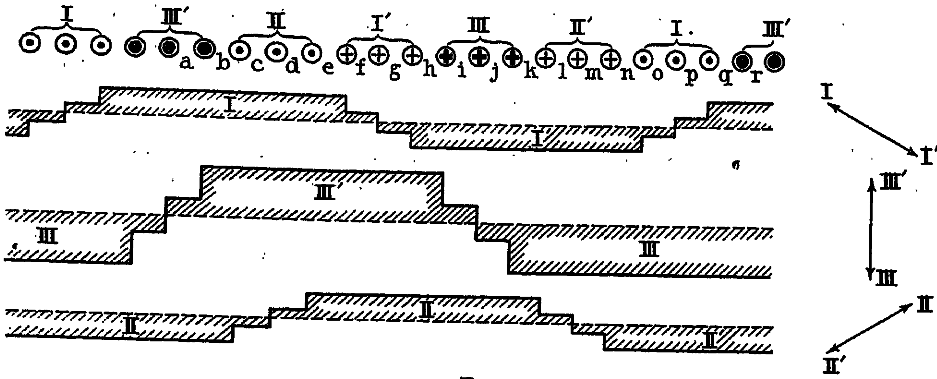
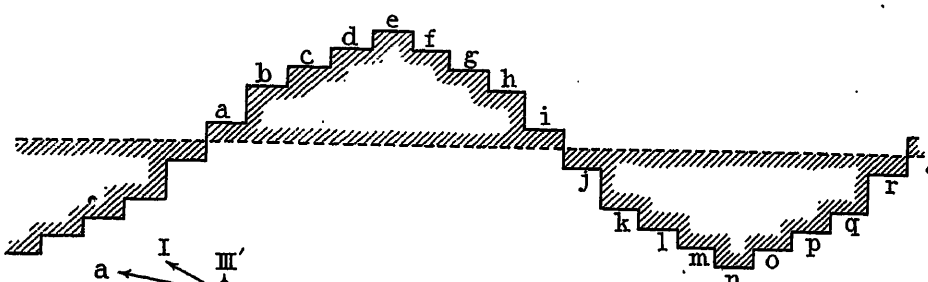


Fig. 5.



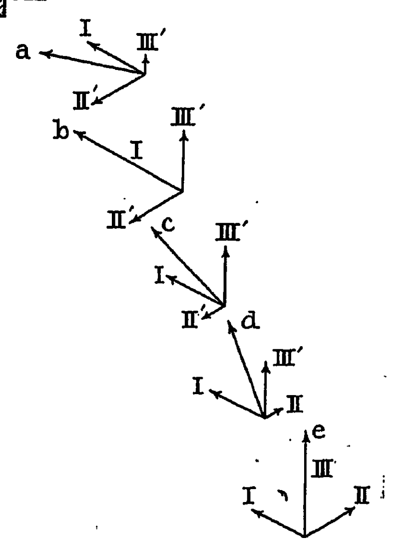


Fig. 6.

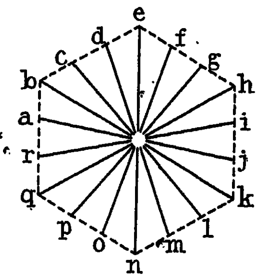


Fig. 7.

The apparatus so far described is suitable for demonstrating simple pulsating or rotating M.M.F.'s, such as occur in an induction motor on no load, but in a modified form it may be used to represent the resultant M.M.F. in the air-gap of an induction motor on load. Fig. 12 shows a stator winding having two slots per pole per phase and a rotor with three slots per pole per phase, both windings being full-pitch. The rotor is shown in such a position that the rotor phases are opposite the corresponding ones in the stator. The stator currents are given by the vector diagram in Fig. 13. Let the angle of lag in the primary circuit be 30° so that the E.M.F. E_2 in phase II is a maximum. The vector diagram of stator and rotor current, so far as phase II is concerned, will then be as in Fig. 14. From the primary current I_2 and the magnetizing current I_m we find the rotor current I'_2, and hence draw the vector diagram of the rotor currents in each phase in Fig. 15. The radial diagrams for plotting the M.M.F. curves can now be constructed as in Figs. 16 and 17. Normally the M.M.F. of the rotor opposes that of the stator, but since we want to show the difference between the two curves, we invert one curve, say that of the rotor, and plot the curves as shown in Fig. 18. The resultant M.M.F. at any point is then given by the vertical distance between the two curves.

Now consider that the radial diagrams in Figs. 16 and 17 are the axial projections of spindles carrying vanes. The shadows of these vanes cast by a beam of light in the direction across the spindles, shown by the arrow, would project the M.M.F. diagrams in Fig. 18 superimposed as shown. For this purpose the vanes must be transparent. In the device used by the author each vane is made of a couple of thin spokes with a thread or wire stretched across the ends, as in Fig. 19. In order to show the movement of the field with the rotor fixed, both spindles must be rotated uniformly at the same speed. Anti-clockwise rotation causes the field in this case to move to the right. In order to show

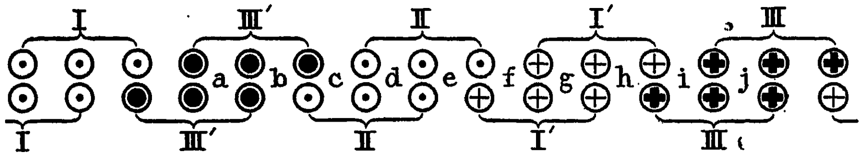


FIG. 8.

TABLE 2.

Vane	Components of phase M.M.F.'s						Resultant			Angular position
	Vertical			Horizontal			Components		Radial length	
	I	II	III	I	II	III	Vertical	Horizontal		
a	$\frac{1}{2}$	$\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2}\sqrt{3}$	0	$-\frac{1}{2}\sqrt{3}$	$\frac{1}{3}$	$-\sqrt{3}$	1·76	180° − 10° 54′
b	$\frac{1}{2}$	1	$-\frac{1}{2}$	$-\frac{1}{2}\sqrt{3}$	0	$-\frac{1}{2}\sqrt{3}$	1	$-\sqrt{3}$	2	180° − 30°
c	$\frac{1}{2}$	1	$-\frac{1}{6}$	$-\frac{1}{2}\sqrt{3}$	0	$-\frac{1}{6}\sqrt{3}$	$1\frac{1}{3}$	$-\frac{2}{3}\sqrt{3}$	1·76	180° − 49° 6′
d	$\frac{1}{2}$	1	$\frac{1}{6}$	$-\frac{1}{2}\sqrt{3}$	0	$\frac{1}{6}\sqrt{3}$	$1\frac{2}{3}$	$-\frac{1}{3}\sqrt{3}$	1·76	180° − 70° 54′
e	$\frac{1}{2}$	1	$\frac{1}{2}$	$-\frac{1}{2}\sqrt{3}$	0	$\frac{1}{2}\sqrt{3}$	2	0	2	90°
f	$\frac{1}{6}$	1	$\frac{1}{2}$	$-\frac{1}{6}\sqrt{3}$	0	$\frac{1}{2}\sqrt{3}$	$1\frac{2}{3}$	$\frac{1}{3}\sqrt{3}$	1·76	70° 54′
g	$-\frac{1}{6}$	1	$\frac{1}{2}$	$\frac{1}{6}\sqrt{3}$	0	$\frac{1}{2}\sqrt{3}$	$1\frac{1}{3}$	$\frac{2}{3}\sqrt{3}$	1·76	49° 6′
h	$-\frac{1}{2}$	1	$\frac{1}{2}$	$\frac{1}{2}\sqrt{3}$	0	$\frac{1}{2}\sqrt{3}$	1	$\sqrt{3}$	2	30°
i	$-\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}\sqrt{3}$	0	$\frac{1}{2}\sqrt{3}$	$\frac{1}{3}$	$\sqrt{3}$	1·76	10° 54′

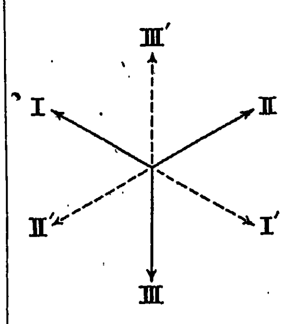


FIG. 9.

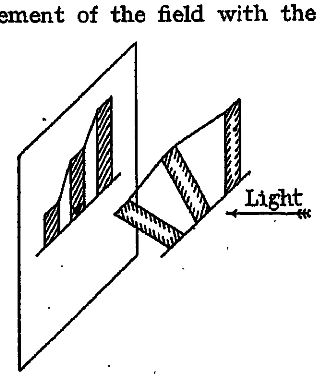


FIG. 10.

the movement with the rotor revolving it is necessary to move the spindle carrying the rotor vanes in an axial direction, i.e. into the paper in Fig. 17. Synchronous

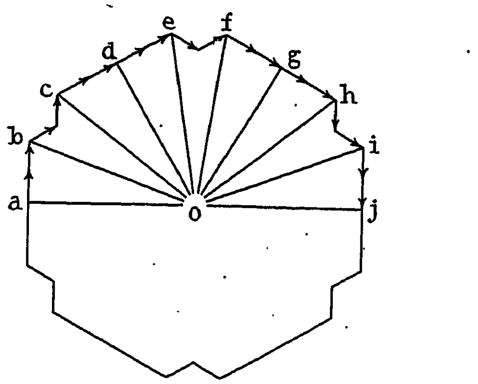


FIG. 11.

speed is shown by moving the spindle along without rotation in the direction of, and at the same speed as,

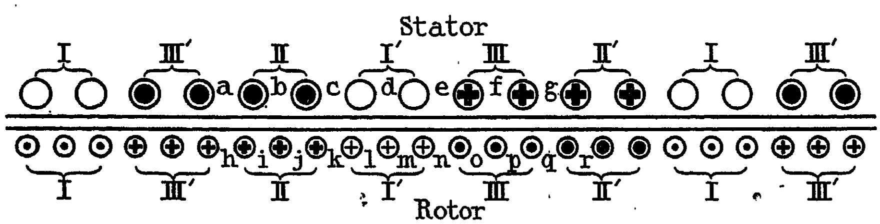


FIG. 12.

the stator field. Slip is shown by moving the spindle at a speed greater or less than that of the stator

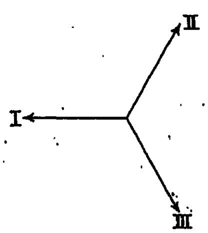


FIG. 13.

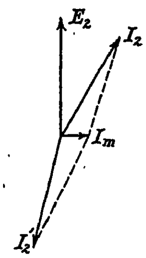


FIG. 14.

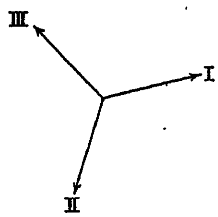


FIG. 15.

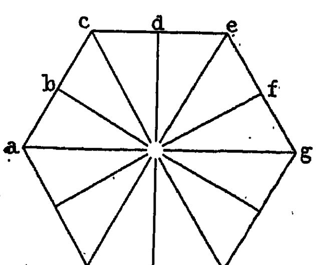


FIG. 16.

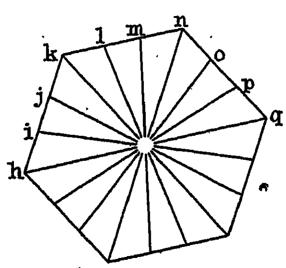


FIG. 17.

field by the amount of the slip, and rotating the spindle at such a speed and in such a direction that the phase relationship between the stator and rotor field is maintained. Thus, if the slip were positive the spindle

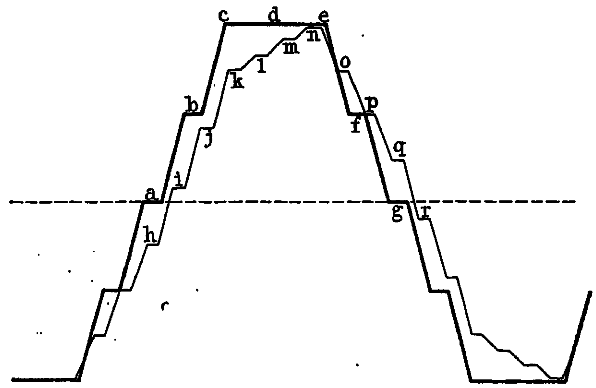


FIG. 18.

would have to be given a small anti-clockwise rotation.

The device used to produce gliding alone, or gliding and rotation combined, is shown in Fig. 20. The spindle s_1 carries the stator vanes and s_2 the rotor vanes. On s_1 is fixed the pulley p_1 of diameter d. This pulley is detachable and can be replaced by others of different diameters. For showing synchronous speed d must be such that πd equals the distance along the shaft which represents one cycle. To represent a slip of,

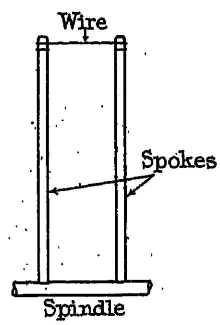


FIG. 19.

say, 5 per cent, d would have to be 5 per cent smaller. A negative slip such as would occur in an induction generator would require d to be 5 per cent larger. A cord is attached to the shaft at a, carried along parallel to the shaft to the eyelet at b and thence round the pulley p_1, so that as s_1 rotates it draws s_2 along at the required speed. Rotation of the shaft s_2 is produced

by the pulleys p_2 and p_3. The pulley p_2 revolves on the sleeve c attached to the carrier. The shaft s_2, which has a long feather, f, on it, passes through c and bears on the disc g attached to p_2. The disc has a key-way to fit the feather. The shaft can slide through p_2 in an axial direction whilst it is rotated by the pulley p_3 on s_1. The pulley p_3 is detachable and can be replaced by others of different dimensions for different slips.

To show the rotor stationary, p_3 must have the same diameter as p_2. For synchronous conditions the belt from p_2 to p_3 is removed and the pulley p_2 held stationary, as the shaft s_2 must not rotate. For a slip of, say,

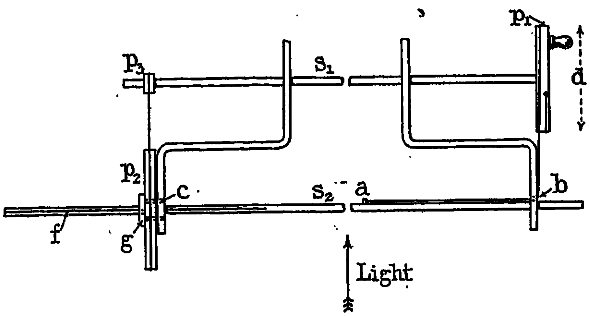


FIG. 20.

5 per cent the pulley p_3 must have a diameter equal to 5 per cent of that of p_2.

A useful addition to the apparatus is an arrangement to show the variation of the ampere-conductors per slot in the stator and rotor as the M.M.F.'s vary. This can be done by placing a drawing of the stator slots on the upper part of the screen and showing the variation of current by means of the shadows of vanes on a spindle rotating at the same speed as s_1. Each vane is opposite a slot and of radial length proportional to the maximum ampere-conductors per slot. For the rotor the spindle carrying the vanes is arranged for axial motion and rotation in the same manner as s_2, and a drawing of the rotor slots is placed on a slide which is drawn along at the same speed as the spindle s_2.

Very often only a simple demonstration is required, without the complication of the teeth. For example, the

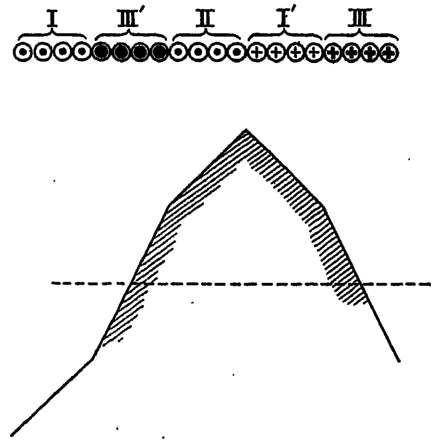


FIG. 21.

M.M.F. curve of a creeping three-phase full-pitch winding such as is shown in Fig. 21 can readily be shown by placing a number of spokes along the spindle at equal distances apart and spaced at angles of 60° round the spindle so that their projections along the spindle are radii to the corners of a hexagon. The ends of these spokes are then joined by straight, stretched pieces of wire or thread.

DISCUSSION ON "THE POSSIBILITIES OF TRANSMISSION BY UNDERGROUND CABLES AT 100 000/150 000 VOLTS." *

SCOTTISH CENTRE, AT GLASGOW, 12 DECEMBER, 1922.

Mr. A. E. McColl: Jona, at the International Electrical Congress in 1904, described a rubber paper-graded cable, which was built by Messrs. Pirelli of Milan. This cable had, I believe, four gradings, and was designed for a working pressure of 75 000 volts. By interposing insulating material of varying specific inductive capacity in layers, a high electric strength is obtained. The choice of suitable materials is, however, rather limited, and the strengthening of the cable on this principle is not a commercial proposition, owing to the price of the materials available. Mr. Beaver † in 1915 put proposals before us for an intersheathed cable, and this certainly looked more promising than the original proposals of Jona and Russell. One difficulty in the intersheath method appears to be that the intersheath, being comparatively light, runs the risk of fusing or overheating due to the passage of large capacity currents on long lengths of cable. Further, it seems to me that any attempt to anchor the potential on the inter-sheath scheme will necessitate, on long cables, either resistances or transformers of large kVA capacity to absorb the energy in the capacity current. The author's cable seems to be an advance on the previous inter-sheath type, in that the intersheath is now employed to carry actual load current and the dimensions for the same maximum stresses are reduced. We can raise the pressures by employing single-core cable, but a certain loss is entailed, due to the sheath. The continuity of the sheath may be interrupted at frequent intervals, in order to suppress the secondary current which naturally tends to flow. With large currents, however, and increased spacings between conductors, considerable potentials may be obtained on the open-circuited sheath. The safer method, therefore, seems to be to incur the loss caused by short-circuiting the sheath at regular intervals. In this connection I should like to have the author's estimate of the increased loss in his cable due to the short-circuited sheath. I do not think that the author is correct in assuming that the capacity of the cable can be increased by releasing it of the charging current, as this relief would apply only to the supply end, the receiving end still requiring to transmit the wattless current between the capacity of the cable and the inductive load at the remote end. One of the most interesting parts of the paper is the comparison between 30 000-volt and 100 000-volt transmission. I do not think that the comparison is altogether fair, as a less expensive scheme could be made out for the 30 000-volt transmission. £1 000 000 is a large sum to spend on the transmission of 50 000 kW a distance of 30 miles, and in this country, where water power does not count, a separate station would in all probability be the better proposition if the conditions are such as to preclude the possibility of overhead lines. The use of cable such as the author has described is more likely to be of value in linking up an overhead line where intermediate stretches are, on account of local conditions, prevented from continuing overhead.

Professor G. W. O. Howe: The fundamental idea of the proposed system is a very sound one. It is well known that the weak point of high-voltage cables is the fact that the inner layers are stressed very much more than the outer layers. I am not very clear about the author's object in the first three or four pages of the paper, in which well-known results are apparently reached by a roundabout and approximate method, whereas the results can be obtained accurately with much less trouble. The author mentioned that, knowing the loss in the lead sheath and also its resistance, the current in the lead sheath could be calculated. It seems to me, however, to be a complicated calculation, since, after finding the loss in the lead sheath, one requires to know the distribution of the current in the lead sheath before that current can be calculated. The distribution of the current over the section of the sheath is by no means a simple thing to determine. I do not know whether the statement occurs in the paper but it was made by the author when expounding the paper. He made rather a strong point of the heating at that part of the cable which is nearest the conductor. Has it occurred to him that, instead of winding concentric conductors round a large central core, he might wind them round a lead water-pipe and pass water through the pipe? I am afraid that this will not impress the mains engineer as being a happy idea, but I do not know that it is any more fearsome than some other proposals in the paper, and I do not know that the mains engineer would be very much more worried with the water-pipe than in making and maintaining the 100 000-volt cable joints. There are one or two details of nomenclature to which I should like to call the author's attention. On page 222 the capacity of air is given per cubic cm, as if it were a function of the volume, instead of per cm cube; while on page 223 the author uses the term "specific resistivity." The resistivity is the specific resistance. On page 222 the author starts from the logarithmic formula and proves that the current is *approximately* constant; now as a matter of fact the logarithmic formula is based on the assumption that the current is the same throughout the dielectric. In Fig. 3 $R = 22$ cm and $r = 0 \cdot 65$; $R/r = 34$, therefore the capacities of two thin layers of the dielectric, one on the outside and the other on the inside, will be in this ratio and, the current being the same, the voltages must be inversely proportional. Assuming a constant power factor, the heat developed per cubic cm will be

* Paper by Mr. A. M. Taylor (see page 220).
† *Journal I.E.E.*, 1915, vol. 53, p. 57.

34^2 = 1 150 times as great at the inner as at the outer surface. This reasoning is much simpler than the method followed in the paper, by which the ratio of 800 is obtained by taking ½ cm layers.

Mr. A. F. Stevenson: When Mr. Beaver read his paper in 1915, I asked for evidence of paper insulation having broken down, due to the inner layers being too highly stressed. We are still waiting for it. I think that it is more economical to use the ordinary strand than the hemp-cored, and thicken the insulation to give the same overall diameter. According to our present knowledge, six single cables would be more economical than two triple concentric cables for 100 000-volt transmission.

Mr. D. Berry: In the slides shown by the author there was an example of a single cable with a hempen core. It occurs to me that should a fault develop and moisture get in, this cable would break down. I understand that there has been some trouble in connection with the French cables, this trouble being attributed to mechanical damage. Our experience on a voltage of 20 000 with single cables has been that mechanical damage is not unlikely; the cable is so flexible that it is easily damaged, and sufficient care is not always exercised in the bending or handling. This is one objection to the use of single cables for high voltages. For voltages below 50 000 I do not suppose that methods other than those adopted at present are required, and I understand that a 50 000-volt three-core cable has been laid and is operating successfully. While I do not think that transmission by underground cables at 100 000/150 000 volts is of immediate moment, the matter raised by the author is of great interest, and I should be glad if he would give further particulars in regard to the insulation which he proposes that the cable makers should adopt for his cable. I should also be glad if he would indicate what we might expect in the case of a number of cables laid in a nest of ducts. It may be that in coming away from a station the cables are laid for some distance in ducts, and it is therefore to be expected that a great amount of heat will arise when the ducts are fully occupied. The cumulative effect due to the interaction of temperature and dielectric losses on the heating of the cables may be a vital factor at the high voltage proposed, and I should like the author's assurance that perfect safety, at any rate, can be looked for from, say, a number of cables of his design laid in the duct line for a certain distance.

Mr. A. P. Robertson: Fig. 13 shows the method of finishing-off the end of the cable so as to reduce the potential gradients at the approach to a joint, and it is stated that this is performed at the makers' works. It is not always possible to know exactly the length of a cable and where the joint will be. It looks rather a difficult joint. If a cable had to be cut, could the special insulation be put on in place? Fig. 11 is very complicated. The connections on a rotary converter are usually considered to be complicated, but as they are all in one station and close to each other it is a comparatively simple matter to check them; but in the case under consideration there are some 30 miles between the different sets of connections and, apart from the cost of these transformers and the space taken up by them, the risk of making a wrong connection seems to me to be very great. If it were only to be done twice, i.e. at each end of the cable, it is possible that no mistake would be made, but the author mentioned that on the route there may be tappings taken to substations. Would all these connections have to be made again at every substation? If so, the system would be very complicated.

Mr. C. W. Marshall: Practically the whole of the paper is devoted to the discussion of the question of dielectric stresses in the cables of the author's transmission system, and the actual question of power transmission is dealt with only in the most superficial manner. I am of the opinion that this point should have been thoroughly discussed before the question of dielectric stresses was touched on at all. It may be quite obvious to the author that the six-phase system which he advocates is workable, but he has been unable to convince me that it is so, either in the paper or in his exposition of it at this Centre. If, however, it is granted that the system of power transmission is practicable, I do not think that the objections raised by the *Electrician*—that the protection of the system would be almost impossible—hold, as this could readily be done on the low-tension side of the step-up transformers. From my own standpoint I feel that the paper is in a form which is wholly unintelligible to the majority of the members.

Mr. A. M. Taylor (*in reply*): In reply to Mr. McColl, I may say that I fully appreciated the difficulty of the risk of fusing or overheating the intersheaths during the passage of large capacity currents, owing to a breakdown at any point of the cable. There is no difficulty with these capacity currents in normal working, but it is admitted that during a breakdown they may be large. This difficulty is, however, sufficiently guarded against, partly by the copper section having to be sufficient to carry the ordinary load current, and more particularly by the arrangement shown in Fig. 12, whereby all the onus of transmitting large discharges of current, due to faults in the cable, is put upon the central core, which is of ample section and cannot be damaged by such currents. I do not quite appreciate Mr. McColl's point that "any attempt to anchor the potential on the intersheath scheme will necessitate, on long cables, either resistances or transformers of large kVA capacity to absorb the energy in the capacity current." If he refers to the conditions obtaining under normal working, I may say at once that, as far as I can see, all that is necessary is to have the six-phase transformers of sufficient capacity and sufficiently low reactance to maintain their voltage when passing the normal capacity currents. Under abnormal and breakdown conditions the discharges are, as I have already stated, taken care of by the central core, and in any case I fail to see how resistances would help the matter.

Mr. McColl's remarks in regard to the loss due to short-circuiting the lead sheath at regular intervals appear to be due to a misreading of the paper, because this is the only method considered therein, and the figures for loss given on page 221 are expressly for that condition. Mr. McColl further remarks that he

does not think that the capacity of the cable can be increased by relieving it of the charging current. I think, however, that he has not fully considered Fig. 15, and I would suggest that the principle of subdivision between the different sectionalizations of the line can be continued to any extent desirable.

In reply to Mr. McColl's remark to the effect that a separate station would, in all probability, be the better proposition if the conditions are such as to preclude the possibility of overhead lines, I may say that, for the addition of another £80 000 or so outlay for copper, my scheme could be employed to transmit 100 000 kW, and that under these conditions I assume that the annual charge for interest and sinking fund on the cables for a 30-mile transmission will not exceed about 0·035d. per unit transmitted, i.e. about the cost of transmission of coal. If, however, as I anticipate from recent conversations with cable makers, it becomes possible to employ approximately 150 000 volts in transmission, then over the same cables it will be practicable to transmit 150 000 kW, and under these conditions the capital charge on the cables would be reduced to about 0·018d. per unit transmitted. This would be of the order of only 60 per cent of the charges for coal transmission. Conversely, the distance might be raised to 50 miles and even considerably more, if arrangements could be made for supplying the capacity current in the manner indicated in the paper. The foregoing figures are for a 40 per cent load factor and do not take account of the loss in transmission.

In reply to Prof. Howe, I gather from Clark and Shanklin's tests that the cross component of the current in the lead sheathing is of nothing like the same significance as the longitudinal component. No doubt the cross component becomes more important as the centres of the three cables more nearly approach one another. On the other hand, according to Mr. Dunsheath's tests, even where they approach one another very closely—as in his three-core cable—this effect is not so serious as to be prohibitive. In any case, the losses in Clark and Shanklin's cable "C"—upon which I have based my estimates for the losses in the cable shown in Fig. 1—were obtained by careful measurement and *include* the loss due to these cross currents.

With reference to Prof. Howe's remarks as to the 100 000-volt cable joints, I am assured by two, if not three, cable makers, that they do not anticipate any particular difficulty in this respect. Moreover, the joints in my scheme are not 100 000-volt joints; they merely consist of a succession of joints with 30 000 volts between each, and the outside joint has only 15 000/20 000 volts between it and the lead sheathing.

I would refer Mr. Stevenson to a paper read before the American Institute of Electrical Engineers by Messrs. Middleton, Davis and Davis, in which are numerous cases of cable lengths being broken down due to the stresses being too heavy.

In reply to Mr. Berry, who refers to mechanical damage arising from the cables being too flexible, I think he can hardly have realized that, in the present case, the cables will certainly not suffer from this fault, particularly if they are steel-wire sheathed. With regard to his suggestion that I should give further particulars of the insulation which I propose that the cable makers should adopt for my cable, I would say that this matter has been left with the cable makers, and I believe that impregnated paper, employing a mineral-oil base, is what they would recommend.

In connection with the heating of cables in ducts, I think that Mr. Berry has not appreciated that I am only considering trunk-line transmission along the main lines of railways, where not more than three cables would be together on each side of the railway. These cables would be, preferably, carried above ground and sheltered from the direct rays of the sun, and space would be allowed between them for the circulation of air. I think, also, that he has not appreciated that only six cables would be required to transmit 100 000 kW, and possibly 200 000 kW.

Mr. Robertson, in common with Mr. Berry, has not appreciated the fact that my cables are primarily intended for laying along the sides of a railway track, being carried a few inches above ground, where the position of a joint would be very readily adjustable. I do not see why a selection of cable lengths, all within a foot or two of one another, should not be supplied on different drums in cases where there is any likelihood of difficulty in finding suitable spots for the joints. As regards the final joints leading into the power house or the substation, it would not matter if these came in the ordinary part of the cable, because they would be jointed under exceptionally favourable conditions, and, being so few in number, very particular care could be given to them without undue expense being incurred.

In reply to Mr. Robertson's inquiry as to whether all the tappings would have to be made at every substation, I would suggest that the cables would be simply opened out at the substations and carried to suitable terminals or busbars, and though, of course, considerably greater care would be necessary than in the case of existing systems to see that all the connections were absolutely correct, yet this only occurs at the initial installation of the line, and is, I am sure, not beyond the capacity of many of our erecting engineers. The joint shown in Fig. 13 looks unnecessarily complicated, because at the time when that figure was prepared I was considering lead intersheaths under both the outer and intermediate cores.

I submit that the complications which Mr. Robertson sees in connection with Fig. 11 will disappear on better acquaintance with the scheme.

In reply to Mr. Marshall, I believe that a few words with me would lead him to withdraw the statement that he is not satisfied that the six-phase system is workable. I have found that in all cases where I have had an opportunity of discussing the matter in detail with any engineer, the difficulties at once disappear. If Mr. Marshall will communicate with me direct, I shall be very pleased to endeavour to take up with him any points which he may find difficulty in accepting. From my own point of view, I cannot see any practical difficulty in the matter of the transmission of the power. I have looked quite carefully into the question, both by myself and in conjunction with other engineers, and no slip in my deductions has yet been pointed out.

I regret if the point has been badly presented, but my reply to this must be that, having satisfied myself that the six-phase transmission was perfectly workable from the point of view of transmitting the power, it became of prime importance to demonstrate where I had effected real progress (in the voltage that might be employed), as otherwise my critics would have said that what I was bringing forward produced no effective result beyond what could be effected by ordinary methods with much less complication.

I submit, however, that if I have succeeded in trebling the voltage which can be obtained with ordinary methods, a small amount of complication in the initial connecting up will not militate against the scheme, in view of the advantages effected by such an increase in voltage.

Mersey and North Wales (Liverpool) Centre, at Liverpool, 15 January, 1923.

Mr. A. E. Malpas: As regards the subject of underground cables to work at 150 000 volts, the usual limit of diameter for an armoured cable is 4 in., any greater value involving serious risk of cracked insulation. It is quite probable, therefore, that a cable with an intermediate lead sheath such as the author proposes, after having been rolled on and off the drum would contain incipient cracks which might not be noticeable under a pressure of, say, 45 000 volts, but which might easily lead to breakdown under the higher pressure, more particularly when the effect of surges is taken into account. I should like the author to say why he finds it necessary to introduce the intermediate lead sheathing below the outer conductor of the cable. It would almost appear that as the lead is at the same potential as the copper, the latter itself could have been used for the purpose in view and the lead sheathing suppressed. Assuming for the moment that the method suggested be feasible and that the estimate of cost given in Appendix E be correct (I have no means of checking the latter), then the cost of the capital charges at $7\frac{1}{2}$ per cent is 0·55d. per kWh on a relatively short line of 30 miles. The cost of the installation amounts to 7s. 6d. per kW per mile, which seems a low figure. In his recent address * our Chairman quoted the case of a 250-mile transmission line in America on which the transmission charges, including capital and depreciation, amount to only 0·16d. per kWh, so that on this basis an undergound cable of equal length and voltage would increase the cost of power by 4·4d. per kWh, or nearly 30 times as much as in the case of transmission by overhead lines.

Mr. W. Holttum: The development of paper-insulated cables has led to the use of increasingly higher values of maximum stress in the dielectric, until it now appears that we are within sight of the limiting voltages of transmission by impregnated paper-insulated cables due to the limit of dielectric stress having been reached. In this paper we have an attempt to increase the possible voltage of transmission by other means. The author has shown very clearly in Section III the inherent disadvantages under which the dielectric of a cable works, owing to the concentration of stress and heat in the dielectric near the copper surface, and he attempts to overcome this by the use of intersheaths. The paper affords a very interesting object lesson of the kind of arrangement which results from such an attempt. Fig. 5 illustrates an application of the principle of intersheaths and clearly shows that, while some redistribution of stress is obtained, the current carried by the outer two cores is at a lower voltage than that in the centre core, i.e. the copper in the outer two cores is carrying less power per square inch of cross-section than that in the centre core. In the second paragraph of Section V the author states that by his system all the cores are utilized " equally for the passage of heavy load currents without seriously diminished voltage on each circuit." This seems to be a vital point in the whole scheme, and I contend that whatever is gained by the redistribution of voltage gradient in the dielectric must necessarily be counterbalanced by a lower effective working voltage of a portion of the copper, and any apparent gain is entirely illusory. The method of jointing in which the end of the cable is prepared in the factory as shown in Fig. 13 prevents any adjustment of joint positions in laying except by burying superfluous cable, and in some places this feature would be a serious inconvenience. The protection afforded by the extra sheath is apparently lost at joints, where penetration of the outer sheath would allow moisture to enter the middle of the cable. In addition, jointing would be difficult and costly. I should like to comment in detail on the conclusions* given in Section VII, and I suggest that on examination they do not show very much in favour of the system. The first four points emphasize reliability only. It may be argued that the reliability of ordinary three-phase cable transmission is satisfactory, and probably as great as that in the author's system, considering that several cables would have to be used to transmit sufficient power to justify its use, and that not more than one cable would be likely to break down at once, in which case one of the ordinary type could be replaced more simply than one of these special cables. Conclusion (5) applies in some measure to any three-phase cable, and on a 30-mile line very considerable power-factor improvement would be effected by the capacity of ordinary three-core cable. Conclusion (6), as already suggested, is compensated for by the reduced power transmitted per square inch of copper section of the outer cores. Conclusions (7) and (9) appear to require further explanation, and in any case are light-load advantages only; the same advantages would appear to be gained in ordinary transmission with a number of cables by switching in only sufficient cables for the load. Conclusion (10) does not appear to offer any advantages over an ordinary system which would be extended to deal with a growing load by adding more cables. Conclusion (11) offers no advantage in view of the economy of three-core construction on

* See page 31.

* Since superseded by others which will be found in the paper as printed in the *Journal*.

the one hand, and on the other the fact that with 100 000-volt single-core cable the core would almost certainly be made solid with a view to making use of the whole copper section. Conclusion (12) is merely negative. This leaves only conclusion (8), which appears to be much more than counterbalanced by the three disadvantages stated in the paper. I would suggest that the system described in the paper would be more easily understood if Fig. 7 were given in greater detail showing exactly how the transformers are individually connected and how the three-phase supply is fed in.

Mr. T. D. Clothier: Many of the diagrams and other matter in the paper bear evidence of evolutionary stages of what is presented as the main subject; for instance, Fig. 13 illustrating the suggested cable end, apart from being a separate idea, shows two inner lead sheaths, three in all, there being no reference to these elsewhere. The purpose of other diagrams is hardly apparent, and those essential are insufficiently explained. There are apparently four transmission systems, three being similar and described as six-phase, but they seem to be really three-phase six-wire combinations at 60 000 volts across each separate phase, there being no interconnection at the middle position. Each of these similar parts is referred to in the paper as a "hexagon" and is repeated three times; except as regards the selection of the common earthing point the author has made this reasonably clear. Here, however, I at least have been unable to decide where and how the fourth system referred to as the "major star" is connected in or superimposed upon the two inner conductors in each of the three systems. At first, Fig. 7 seemed to give a key to these transformer connections; on examination, however, it appears that two single-phase supplies with a 30° difference of phase are separately produced from somewhere and superimposed on two "hexagons." I suppose that in the case of the three-phase combination all the circuits are in some way derived from one simple three-phase generated supply, and that all are again re-convertible. An ordinary diagram of connections would have been very much appreciated. The author only compares the cost for the proposed system with that of transmission by 10 cables at 30 000 volts, and no comparison is made with the cost of a straight 100 000-volt system with earthed neutral using 57 000-volt single-core cables, it being presumed probably that these cables cannot be manufactured. It is shown in the paper, however, that three sets of these cables, any two of which would be sufficient to transmit the power under consideration, would contain only 1·665 sq. in. of copper section against 2·532 sq. in. in the author's six cables, hence, if this type of cable can be made, it will no doubt summarily dispose of any application of the author's proposals. An attempt to reconstruct the system from the schedule of equipment was no more successful. A total of 42 transformers, of four sizes and ratios, with an aggregate capacity of 227 000 kVA as compared with 30 similar transformers of 126 000 kVA proposed for the 30 000-volt system, seems to require some further explanation. The diagram of the cable in Fig. 6 gives a misleading impression of a section of the cable, for the outer conductor is placed upon a lead sheath of over 3 in. diameter, but it has an area of only 0·08 sq. in. and consequently will be made up of rather fine strands; the area, for instance, compares with 0·107 sq. in. for the intermediate conductor. Again, the finance (at the end of Section VI) based upon the estimated annual saving of £375 is certainly faulty, and as it is not essential to the merits of the main theme it seems regrettable to have introduced it. The essential proposition contained in the system seems to be to transmit one half of the power at 60 000 volts through 6 conductors, arranged in pairs of triple-concentric cables with a common neutral point in the centre of one phase, and to use the intermediate and outer conductors for the purpose of splitting the dielectric into thinner sheaths than would otherwise be necessary; and at the same time to superimpose additional current upon the inner cores in order to transmit a similar amount of power at a pressure of 100 000 volts. The proposal seems to be quite feasible and an advance on previous suggestions to use intersheaths for this purpose, but its commercial application depends largely upon the possibility of producing reliable single-core cables capable of working at the same pressure without the intersheaths.

Mr. A. B. Mallinson: In his opening remarks the author speaks of having had offers from two or three cable makers to make and lay high-pressure cables which would be guaranteed for one year; such a short period would be totally inadequate to secure consideration for a proposition. I entirely endorse the remarks made by Mr. Holttum about the method of finishing-off the ends of a cable, as shown in Fig. 13. One can imagine the hopeless position of the mains engineer who has to have the finished joint on the end of his main made at the makers' works. It is utterly impossible for anybody to give a definite length for a cable to be laid underground, as one may come across obstructions which mean diversion when the ground has been opened up. One has to assume, therefore, that there would be little loops to be accommodated at the ends, which would certainly not be advantageous. To my mind the important part of the paper centres on the conclusions given on page 232; if all the claims can be substantiated they certainly constitute very important and valuable advantages, but the disadvantages compared with a 30 000-volt three-core line are equally vital. I particularly notice that the induced currents in the lead sheathing are considerably increased where the cable centres cannot be kept within 6 or 7 inches. I cannot see how the author can get his cables so close, unless they are laid on top of each other, which would be unsatisfactory; and further, even if this could be done, it would mean quite a large cross-section for the main as a whole, difficulties in underground laying being thereby increased.

Mr. W. P. Fuller: I think that the author has exaggerated the effects of temperature on cables. It does not seem clear whether the remarks in the paper and the curves shown on the lantern slides refer to d.c. or a.c. resistivity. The fact that the d.c. resistivity falls rapidly as the temperature rises is a matter of no great moment. If the curves refer to the a.c. resistivity they must refer to somewhat old cables. A modern high-voltage cable can be made to have a very nearly constant

power factor, and less than 0·01 over the working range of temperature, and consequently the dielectric losses are very nearly independent of the temperature. With regard to intersheaths, it is a mistake to aim at obtaining a uniform stress, because the breakdown of a dielectric is not altogether a function of the maximum stress. It must be looked at in a different light from that of a metal structure failing under steady loading. In general, as the diameter of the conductor is increased the stress must be reduced if the factor of safety is to be preserved. It is unfortunate that in the author's intersheath cable the voltages are 60° out of phase. Had there been no intersheaths at all, 60 000 volts applied between core and lead would produce across the ½ inch of dielectric next to the core a potential difference of 33 000 volts. As it is 30 000 volts with the intersheaths present, the gain from their use is negligible.

Professor E. W. Marchant: On page 222 is given the result of some calculations of the condenser current per foot of cable across different sections of the dielectric. The power factor of the dielectric has been assumed to be the same throughout, and under these conditions the capacity current must be the same across all sections. On page 223 the author refers to the increased dielectric loss in the inner sections of the dielectric of his cable. This result is, of course, very well known. The energy stored in a dielectric is proportional to the square of the dielectric stress and, therefore, if the power factor of the dielectric is constant it follows that the power loss due to dielectric hysteresis is proportional to the square of the dielectric stress. The method described of using intersheaths on the cable in order to reduce the maximum dielectric stress on the inner portion of the insulation is, of course, comparatively old. It is undoubtedly a great saving to diminish the dielectric stress in the inner layers of the cable. This may be done either by using material of greater specific inductive capacity or, as Mr. Beaver suggested, by using intersheaths. It seems very doubtful, however, whether it will be worth while to try to diminish the current which is carried by the intersheaths by introducing auto-transformers at different points along the cable to supply the necessary charging current. In this connection Mr. Torchio's statement quoted on page 228 may be aptly quoted, i.e. "The assuring of reliable operation is vastly more important than getting the maximum rating out of a certain mass of metals." With regard to the system itself, it is difficult to follow it completely from the paper. The closest analogy to it would seem to be a three-wire a.c. system with the centre point of each phase earthed (see Fig. E). The author proposes to use an earth on one side of his "hexagon" of which the other side is about 60 000 volts above earth, whilst the other pair of cables is about 60 000 volts below earth. In the arrangement which he describes, the potential difference between the inner conductor and the first intersheath conductor would appear to be 30 000 volts; between the first intersheath conductor and the next one it will also be 30 000, and between the outer intersheath conductor and the sheath there is a further 17 800 volts, so that the total pressure, added numerically between the inner conductor and the sheath, is 77 800 volts. Of course the pressures between the conductors are not in phase with one another, but from the point of view of dielectric stress this is not of importance. If the cable were working as an ordinary 100 000-volt three-phase cable with the centre point of the phase earthed there would be a total difference of pressure between the phase and the earthed middle point of only 50 000 volts as compared with the author's 77 000 volts, and thus there would be less stress on the dielectric than in the suggested arrangement. If the intersheaths are used for conveying the power as well as for equalizing the pressure, the copper cannot be used so efficiently as if the whole of the power were transmitted at the higher pressure. As Mr. Holttum has pointed out, the actual power transmitted on each side of the system depends on the pressure from earth to the conductor and the current through the conductor (if the power factor is unity), and no arrangement could be more economical, as far as copper section is concerned, than to send the whole power through the conductor which is at the greatest pressure above or below the earth. In order to obtain an accurate estimate of the merits of

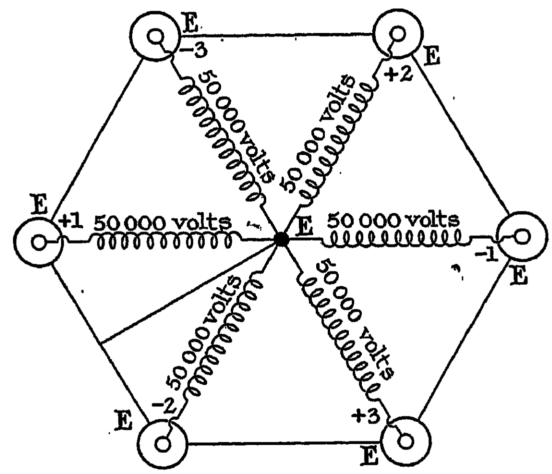


Fig. E.

the proposed system it ought, I think, to be compared with that shown in Fig. E which is really a six-phase system of transmission, lacking, however, the special arrangement of intersheaths given by the author. Intersheaths can, of course, be used with this arrangement, but in this case they would do nothing more than control the voltage gradient through the dielectric. If the author will compare his system with the one indicated above, I am sure that he will find that a greater cross-section of copper will be necessary in his system than in that shown in Fig. E.

Mr. J. W. Warr: Considering the new method from the consumer's point of view, I notice that the single-phase transformers will be designed at only 0·7 power factor, whereas, under existing conditions, the figure is 0·8. The power factor at the distributing centre determines that throughout the whole of the distribution system, even to the consumer's terminals. During the past 12 months there has been considerable discussion on the correction of power factor, and it has been generally agreed that the consumer must help the

supply authority by keeping the power factor within reasonable limits. In the first place it would be interesting to note what the power factor will be from transformers originally designed at 0·7 when they are subjected to an inductive industrial load of comparatively small magnitude. For instance, in the present three-phase systems of distribution it is quite a common condition with a comparatively small load of 500 kW for the power factor to be between 0·65 and 0·7. Unless the electrostatic capacity of the cables raises the power factor, the consumer will be further penalized by having to compensate even more than at present. The figures suggest that a cheaper system of transmission is to be the result, but I consider that we should not sacrifice too much in this direction if the new proposals are in any way complicated. There is at the present time sufficient complication in connection with large distribution networks. The question of reliability is another important item from the consumer's point of view, particularly in certain industries. Inconvenience and endless expense are occasioned by an interruption at the distribution or main generating centre. A 20-minute failure will generally set the industry back for a whole day, and on these grounds, and on account of complicated switchgear, breakdowns are more severe than with the lower pressure supply. From the mains engineer's point of view the proposed system is no doubt a complicated one. Any mains engineer knows quite well the care and thought that is necessary in looking after a large network. Whatever method of distribution is employed some fault will develop, a failure of insulation producing a short-circuit either between conductors or to earth. Then I notice that there is a question of the distance apart of the single-core cables. Providing the distance between the centres does not exceed 7 in., the sheath losses will not be perceptible, but I should like to point out the space that is generally available in public streets for lighting and power cables. Frequently diversions have to be made for accommodating even the smallest high-pressure cable, and my experiences have been such that the direction has been a cause of great anxiety. Where there is already in existence a large network of cables, Post Office telephone cables, hydraulic mains, water mains, gas mains, etc., the available area is very restricted, and I doubt whether the author will succeed in getting through the thickly populated areas which must be traversed when laying trunk mains to the rural districts. At this point I should like to turn back to the comparative costs (see Appendix E) of the 30 000 and 100 000-volt systems. Apparently the great saving between the relative systems is shown to be in the laying of the underground cable. I notice, however, that in Scheme "B" (100 000 volts) there has been no special item set aside for excavating and reinstating the streets, as shown in Scheme "A" (30 000 volts). Are we to understand that the £400 000 for cables includes the excavating and reinstating? I would suggest that ample margin should be left for contingencies when dealing with a group of cables as proposed, compared with that in the case of an ordinary three-core cable. It is often only with difficulty that one or two three-core cables can be adopted in some roadways. Diversions have proved in the past to be more expensive on these grounds, and ample margin should be made.

Mr. F. Mercer: The author has described an intersheath cable to be used in conjunction with a special system of generation which is intended to make more economical use of cable space than is the case at present. Such a cable, however, is less efficient than a single-core cable having approximately the same cross-sectional area. A single-core 57 700-volt cable having the same diameter of core and thickness of dielectric as the one illustrated in Fig. 1, but having 0·422 sq. in. of copper in the core instead of 0·185 sq. in., should convey a current of 575 amperes without undue temperature-rise (assuming 9-in. centres). At 0·8 power factor this represents a carrying capacity of 26 500 kW per cable, which is more than 100 per cent better than the anticipated performance of the intersheath cable in Fig. 6 which, including intersheaths, has the same cross-sectional area of copper. The following points illustrate some of the disadvantages of intersheath cable: (1) Capacity currents necessitate a very appreciable cross-sectional area of copper for the intersheaths alone; (2) when used for conveying power the intersheaths are operating at lower voltages than the central core and transmit correspondingly less power for a given amount of copper; (3) space occupied by the intersheaths might be usefully occupied by dielectric; and (4) the permissible voltage gradient for the dielectric near the central core or the intersheaths is lower than for a single-core cable, because a thin dielectric necessitates a higher factor of safety. In connection with the table of comparative costs given in Appendix E, it is difficult to understand how 10 three-core 30 000-volt cables are expected to cost £1 000 000 for a 30-mile run, or £100 000 per cable, whilst 6 intersheath cables of approximately the same cross-sectional area are estimated at £400 000, or £66 700 per cable. A more valuable comparison would have been afforded if the estimates given in this appendix had been for the author's six-phase/three-phase scheme and for a three-phase single-core cable scheme, the operating pressure in each case being 100 000 volts.

Mr. A. M. Taylor (*in reply*): Mr. Malpas asks why I introduce an intermediate lead sheathing below the outer conductor of the cable. This outer lead sheathing was for the purpose of providing a means whereby the impregnation of the cables could be done in two stages, but a subsidiary purpose is served as indicated at the top of col. 1, page 229. The lead sheathing can, of course, be suppressed if found unnecessary for the manufacture of the cable.

With reference to Mr. Malpas's remarks as to the cost of the capital charges on the transmission line, I think there is no doubt that instead of 0·55d. per kWh he really means 0·055d. If the transformers, which are common to any system of lin transmission, are omitted, the cost is only of the order of 0·037d. This correction would alter his figure from 4·4d. per kWh on a 250-mile line, to 0·44d. This, however, is not all that may be said for the underground transmission, because from information received from one of the leading cable manufacturers it now seems to be practicable with this system to run the pressure up

to 150 000 volts and with the same six cables to transmit 200 000 kW. On this basis the initial cost of the capital charges on a 30-mile transmission line would amount to only 0·018d. per kWh, and this would compare quite well with the 0·16d. quoted by Mr. Malpas for the much longer overhead line.

Mr. Holttum's preliminary remarks are partly correct and partly based upon a fallacy. It is capable of easy proof that the voltage in the load circuit which traverses the outermost intersheath is 60 000 volts, however near the outermost intersheath may be to the outside lead sheath of the cable, whereas it is demonstrable that in the arrangement shown in Fig. 5 the voltage transmission would be reduced to a ridiculously small amount if such a position were postulated for the lead sheathing. The small diagram (IV) at the left-hand bottom corner of Fig. 9 would have shown Mr. Holttum that it was practicable to increase the above-mentioned 60 000 volts, if necessary, to 80 000 volts, so that it is quite incorrect to say that any gain in redistribution of voltage gradient in the dielectric must necessarily be counterbalanced by a lower effective working voltage of a portion of the copper.

With reference to the cable shown in Fig. 13, the protection afforded by the extra intersheath can, if desired, be continued right up to and into the joint boxes. Mr. Holttum proceeds to demolish, one by one, the "conclusions" at which I have arrived (these have been superseded by others which will be found in the paper as printed in the *Journal*). He passes by the first four items with the remark that they emphasize reliability only, and he suggests that an ordinary three-phase system is just as good on this point. I admit that it is at 30 000 volts; but I have shown in the London discussion that the two systems cannot compare in point of view of capital outlay when powers of 100 000 kW transmitted over 30 miles are considered. He says that conclusion (5) applies to any three-phase cable. It does so in a degree, but the charging current, being in my system approximately double what it is in a three-phase cable, gives corresponding advantages for the purpose considered.

Mr. Holttum dismisses conclusion (6) in a very cavalier fashion, but I submit most definitely that instead of the gains of intersheath being compensated for by the reduced power transmission per square inch on a section of the cores, he has entirely ignored the extent of the gain effected by the use of intersheaths and by the separating of the cables, which in single-phase "intersheathed" cables gives my system an advantage of practically *three times* that of a plain three-phase system, as regards the E.M.F. which may be applied. Now, even if the reduction of the voltage on the currents passing through the intersheaths were 50 per cent, this would still only affect one half of the load (the other half being transmitted through the central cores), and, therefore, is only equivalent to a reduction of voltage of 25 per cent on the whole system, whereas I have just intimated that the *gain* in voltage by the use of intersheaths combined with single cores is 200 per cent.

Mr. Holttum next suggests that conclusions (7) and (9) appear to require further explanation, and in any case are light-load advantages only and can be obtained in an ordinary system by switching cables in and out. The advantage of reducing the capacity current at low loads is so important that in the United States several of the large generators employed in power transmission have had to be made considerably larger than they otherwise would have been, solely because of the supply of large charging current. The idea of switching in and out a large number of cables to adjust the capacity current is not practicable. On 100 000 kW transmission 16 cables would be required and the number of switches to be operated would be 32.

Mr. Holttum considers that conclusion (10) is of no particular advantage, and I am prepared to grant that with an ordinary three-phase system the point is certainly not one of much moment, but I have already shown elsewhere that an ordinary three-phase system cannot compete, from the point of view of capital outlay, with my proposed arrangements, at powers of over 50 000 kW.

As regards conclusion (11), he suggests that there is no gain over ordinary three-core cable from the point of view of the amount of waste room in the cable, and suggests that the economy of three-core construction will compensate for this. I can only say, with regard to the latter, that the estimates which I have obtained from the cable makers prove the contrary. In this connection I suggest that he refer to my remarks in reply to Mr. Sparks in the London discussion. In the same connection he implies that the 100 000-volt single-core cable would compete equally well on this point, and this I am prepared to concede, but in this case I submit that conclusions 2, 3, 4, 7, 8, 9 and 10 (particularly the last-named) have all to be considered in this connection, and there is still more to be said than has been embodied in the "conclusions." Mr. Holttum suggests that my conclusion (12) is merely negative. This is hardly fair, because if the point can be established it represents great possibilities which the present makers of cables have not seen their way to take advantage of, or to suggest. He suggests that all the advantages claimed are quite wiped out by the three disadvantages mentioned. As regards these disadvantages, I would say that the first is somewhat of an advantage, if my system of capacity current can be successfully adopted. The second disadvantage will not obtain when the cables are laid along the sides of railways in the manner which I propose; only three cables need be laid together, the other three can be put on the other side of the railway, and in fact any distance apart that is desired, from the first three. It follows, therefore, that it is only necessary that three cables should be arranged in "triangle" regulation to one another, and this is perfectly easy. I trust, therefore, that I have met the whole of Mr. Holttum's criticism, and that there is no outstanding point which I can be said to have ignored.

With reference to Mr. Clothier's remarks about the superposed currents shown in Fig. 7, he will, I think, find his difficulties cleared up by a reference to Fig. D, given in my reply to the London discussion. He will

there see the source from which is derived the supply spoken of as differing by 30 degrees in phase from the two topmost corners of the hexagon. He will see that all the circuits are quite easily derived from one common system of low-tension three-phase busbars, and will realize that they are all equally easily reconvertible to a common system of low-tension three-phase busbars at the receiving end. Mr. Clothier is correct in supposing that the reason for the omission of a comparison of the cost with that of a straight 100 000-volt single-core cable system was that these cables cannot at present be manufactured. Even if they could be manufactured, however, there are numerous reasons why the supply through the system proposed by the author would be very much more reliable in actual working, some of which are given under the heading "Conclusions" on page 232. It is submitted that, even if the plain single-core 100 000-volt cables can be manufactured, the proposals given in the paper will still be very much more satisfactory for reasons which have been adduced in various places during the discussion.

With reference to Mr. Clothier's remarks as to the number of transformers involved, the reason is one that would apply partly to single-core cables also, and is due to the large amount of leading kVA capacity available, *unless* the lagging component of the consumer's load can be effectively utilized in the manner proposed by the author. In this latter case, as is indicated on page 238, a saving of £75 000 would be involved in the reduced capacity of transformers. The finance of the estimated capital saving of £77 800 is, in my opinion, most essential to a proper understanding of the reasons for the selection of 10 cables of 0·25 sq. in. section as against the 6 cables considered in the proposed system. It is quite true that I omitted the interest on the money invested, but if this be taken into account, and if the 25-year life of the cables be also taken into account, the capitalized value of each 1 per cent loss in transmission can be shown to be of the same order as the figure above given.

With reference to the last point brought forward by Mr. Clothier, namely, that the success of the commercial application of the system proposed depends largely upon the possibility of a suitable single-core non-intersheathed cable being produced, this point has already been dealt with. Briefly, it may be said that a non-intersheathed single-core cable which, for an equal diameter of cable, can be operated at the same voltage as the intersheathed system, is not likely ever to be introduced. Mr. Clothier seems to have lost sight of the fact that it is not necessary that one half of the power should be put through the six-phase system, and that if, for instance, one quarter of the power were put through the latter, the voltage of transmission would be equivalent to a voltage of 90 per cent of the full central-core voltage taken over the combined system.

In reply to Mr. Mallinson, I would refer him, in connection with overhead transmission, to my reply to Mr. Malpas, also to the discussion at Newcastle. With regard to guaranteeing the cables for only one year, it was I myself who fixed this period, believing that it was hopeless to expect the cable makers to guarantee a new cable, about which they knew nothing, for a longer period.

Mr. Mallinson's remarks with reference to the joint shown in Fig. 13 are made on an entirely wrong supposition. He is assuming that I am considering the running of cables along ordinary roads, whereas I am considering their running on short supports some 18 inches above ground on the two sides of a railway line, and where the position of the joint can in most cases be adjusted quite easily. I have suggested elsewhere that a few drums, of lengths slightly greater and slightly less than normal, which might be used in special circumstances, could be supplied. With regard to Mr. Mallinson's remarks that the three disadvantages cited are equally as vital as the advantages cited, and that particularly No. 2 is a serious one, I would remark that my proposals involve only three cables being kept in close proximity to one another; the other three cables could be placed many yards apart from the first three, since each set of three balances out its own field. This also applies to his difficulty about keeping them cool, and to his difficulties about the large cross-section of the main required. Moreover, 16 three-core three-phase cables will certainly take up more street room than would my six cables.

In reply to Mr. Fuller, the lantern slide which I exhibited connecting resistivity with temperature was based upon alternating currents, and I note that it is practically in accordance with a curve very recently given by Prof. Delmar. I do not see the point that, because the power factor can be kept below 0·01 over the working range of temperature, the dielectric resistivity losses can consequently be ignored. If the figure taken for the resistivity in the calculations at the end of the present paper is in the least degree near the mark, the resistivity loss is quite a serious one at the high temperatures, and what we have to consider is not merely the *estimated* range of temperature, but the temperature that may obtain when, through some breakdown of a parallel system, perhaps double the normal load is passed through the remaining system, and it may occur at the time of greatest summer temperature.

In reply to Mr. Fuller's remarks regarding intersheaths, I have already taken up the point of the question of maximum stress in reply to Mr. Dunsheath (see page 248), and am strongly of opinion, after reading the whole of the controversy in America on this question, that we cannot afford to ignore the maximum potential gradient when it is a question of continuous working. With reference to Mr. Fuller's remarks that, owing to the voltages in my system being 60 degrees out of phase, nothing is gained as compared with non-intersheaths, I would point out that this has been dealt with in connection with my remarks in reply to Mr. Dunsheath, where I have shown that the loss due to the obliquity of the vectors is only 15 per cent, whereas the gain due to the use of intersheaths is 220 per cent. Mr. Fuller's remarks that the gain from the use of the intersheaths is negligible are therefore totally unwarranted by the results established in the paper and the discussion.

Replying to Professor Marchant, I would say that,

on a 30-mile line, it is only necessary to introduce what he calls the auto-transformer arrangement (but which I submit is a misnomer) at the extreme end of the line where it forms a perfectly simple and practicable arrangement. Possibly Prof. Marchant has not had occasion to consider such a long line as this is and has consequently not fully appreciated the large amount of charging current to be transmitted, and how important it is that this should be transmitted under the full voltage.

It is quite true that such an arrangement as is given in Prof. Marchant's Fig. E would work perfectly well, but apart from the fact that the full 50 000 volts exists between the central core and the lead sheathing, there would be the difficulty of the junction boxes, in which there is nothing to give any hint of trouble until a total breakdown occurs at one of the latter. The same applies, of course, to the cable itself. Moreover, it is not yet an ascertained fact that cable makers are prepared to supply cables operating at 100 000 volts. Further, it appears that if a breakdown occurred in any one cable it would not only operate the trip gear on the one half winding of the transformer supplying that cable, but the other half winding (if on the same core) would probably be pulled out as well, which would instantly involve the shutting down of the whole system as a three-phase system, whereas under the arrangements I am proposing, with three self-contained hexagons working independently, the pulling down of one hexagon would only put that hexagon momentarily out of circuit, and a few seconds later one of the cables at least could be reinstated. Further, if the fault extended only as far as the outermost intersheath, the probability is that the whole six cables could still be employed after the momentary disconnection of the faulty hexagon. Prof. Marchant's remarks relating to the obliquity of the vectors are quite correct so far as they go, but I have shown elsewhere that it can be easily arranged that only 15 per cent is lost by this obliquity. I have dealt with the question of the use of intersheaths for the conveyance of power in my replies to other speakers.

In reply to Prof. Marchant's remarks that if I compare my system with that shown in his Fig. E, it will be found that the amount of copper is less in the latter, I am not disposed to question that there would be a small amount in this direction, but since taking up this general question of transmission I have ascertained that the amount of copper in the system is not the sole criterion of its cheapness, or the reverse, and the system shown in Fig. E, though interesting, cannot possibly compete with an intersheath system if the maximum potential gradient is to be accepted as any criterion at all for the safety of cable working over very long periods at the highest possible stresses.

I think that Mr. Warr is under a misapprehension as regards the question of power factor. The reason of my transformers being put in for a low power factor is solely on account of the large line-charging current, which affects the step-up transformers at the sending end very materially. If this charging current can be arranged in the way I propose, to benefit the system, then, instead of the consumer being penalized as Mr. Warr suggests, he will get a bonus on account of his poor power factor. Does Mr. Warr realize that the question of distribution is really not touched by my proposals and would remain exactly where it now is, since I revert back to ordinary three-phase currents at the substation? His remarks as to the mains engineer's position also give me the impression that he is thinking merely of a ramified underground system operating at 100 000 volts, which is not my proposal at all. Similarly as regards the area required by the mains, this is because he is considering town distribution, and perhaps because I have not made it sufficiently plain in the paper that I am primarily considering transmission along the main lines of a railway between a super-power station and a general substation at the far end of the line, with possibly intermediate substations feeding the railway itself, but at considerable distances apart. This will explain why I have not included any item for the excavation of streets in connection with the system proposed, the reason being that the cables are merely assumed to be carried some 18 inches above ground on a light structure at the side of the railway, and no excavation is therefore necessary.

Mr. F. Mercer endeavours to show that by employing a cable such as shown in Fig. 1 of the paper and filling in the central parts of the central core with copper, the power can be put through in a much more efficient way than under my proposed system. I would say, however, that if one of the cables goes down, the whole system goes down, and therefore there is no reliability whatever about his proposal. Moreover, I have shown in my reply to the London discussion that a single-core unsheathed cable cannot compete with a single-core intersheathed cable, which latter can be worked at a voltage nearly 100 per cent greater for a given cable diameter and maximum potential gradient. As regards his remark that capacity currents necessitate a very appreciable cross-sectional area of core for the intersheaths alone, I would point out that by the method of transmitting the capacity current shown in Fig. 12, the current required to be transmitted through the central core is virtually identically the same as that required in the case of a single-core cable—in fact, with the 100 000 volt single-core scheme the kVA for charging purposes is 65 700, whereas in my scheme it is 61 200. These figures can be obtained from the calculations given in the paper. I have dealt elsewhere with Mr. Mercer's point about the intersheaths operating at lower voltages. His remark that the intersheaths occupy unnecessary space which could be usefully occupied by dielectric is also beside the point, because copper strip can be employed for the intersheaths. Apart from this, however, I have made calculations as to the actual difference in diameter of cable due to the addition of the intersheaths, which show that his statement is quite untenable as a serious objection. His statement that the permissible voltage gradient allowable is less where intersheaths are employed than for a single-core cable raises the whole question of maximum potential gradient, and I do not consider that to put the matter in this form is a fair statement of the question involved. After a careful perusal of the discussion before the American Institute of Electrical

Engineers on the various recent cable papers, all of which are, in my opinion, of high merit, I do not consider Mr. Mercer's statement to be fully proved, at any rate in the form in which it is given; *in fact in one place it is directly contradicted.*

With reference to the prices of the cables, I may say that I obtained prices from several manufacturers and I have neither given the highest prices obtained for the three-phase cable, nor the lowest prices obtained for the triple-concentric cable. With regard to Mr. Mercer's remark that it would have been better if a three-phase single-core cable scheme had been compared with the scheme put forward in the paper, I may say that there is not at present in existence a three-phase single-core cable scheme operating at 100 000 volts, and I am not certain whether I should have been able to get any guarantees for it in this country, but even if I had succeeded in this there is, in my opinion, no question as to the much greater reliability in operation of a triple-concentric cable the outermost conductor of which is at a potential not very greatly different from that of earth.

DISCUSSION ON "DOMESTIC LOAD BUILDING."*

SCOTTISH CENTRE, AT EDINBURGH, 9 JANUARY, 1923.

Mr. R. B. Mitchell: I have always been a believer in the cultivation of the domestic load, and I have said before on many occasions that the day may come when the domestic load will be of as great importance as the industrial load. It has a feature of continuity which the industrial load does not possess. We have just been passing through a time when the industrial load almost disappeared in the majority of undertakings in the country, and if those undertakings had had a good domestic load to keep them going during the dull times in industry, they would not have felt the effects nearly so much. In Glasgow the domestic load has been cultivated for some years past and we have achieved considerable success in that direction. We have now connected domestic appliances totalling 17 165 kW and the consumption due to these appliances amounted last year to 5 506 000 units. Also, we have in business premises appliances other than for lighting, totalling 15 080 kW. In looking over the paper, I consider the main point in it to be the question of tariffs. I think that the tariff is of the very first importance in developing the domestic load. If one has a suitable tariff, then it is quite right to have propaganda, but propaganda is useless unless one has such a tariff. I quite agree with the author's opinion on page 197 that the fixed charge should be sufficient to cover a consumer's normal lighting costs when the low unit charge is added. Further, I think that the fixed charge should be made high initially, in order that the running charge may be as low as possible. There is one drawback to that system of charging, namely, that to the ordinary consumer it is too great a change. He may have been in the habit of using electricity for lighting only, consuming, say, 50 to 200 units per annum, and paying a comparatively small sum for the service; and he is asked to promise to pay something like £8 10s. before he uses any electricity at all. I think that the ordinary man, particularly in Scotland, will hesitate before he takes on such a commitment. But there is another way of achieving the object: a tariff should be arranged, with a fixed charge and a low running charge, which will lead him on in steps in such a way that he will not notice the increase in his use of the electric service. I agree with the author that the fixed charge which he puts forward should cover the lighting units only—perhaps more than that—and that the demand of the heating and cooking appliances should not be taken into account in making up the fixed charge. It has been thought in the past by many supply engineers that the maximum demand for lighting was not sufficient—that the consumer possibly used a very small quantity of electricity for lighting with consequent low maximum demand—and perhaps 5, 6 or 7 kW for heating and cooking, and that this ought to be taken into account when fixing the maximum demand. It has been proved conclusively now that the domestic load is nearly always in its entirety an off-peak load. One has not to take into account the domestic load in thinking of the power station output in kilowatts. As regards the rate in Glasgow, we have adopted the principle that consumers are asked to pay for a certain number of units at the lighting rate, depending upon the size of the house, and all units consumed over the fixed quantity are charged for at the heating and cooking rate, which at the present time is 1d. per unit. The consumer can secure this rate even if only a very small domestic appliance is installed. He must have some-

* Paper by Mr. W. A. Gillott (see page 197).

thing, even if only an iron, but this gives him a start, and he adds to his installation and later on gets a cooker which, in 99 cases out of 100, converts him completely to an all-electric user. Then, if he wants to go still further and use electricity more liberally, he is ripe for a rate of the description put forward in the paper. I have applied to the accounts of a number of consumers in Glasgow a system such as the author explains, and I find that it can be superimposed on this rate with very great facility and works very well. I adopted a fixed charge such as he suggests, but I got the basis for it by taking a percentage of the rental, and I think that a figure of something like 10 or 12½ per cent would be appropriate. I am quite sure that by and by, with a fixed charge of that amount and a running charge of ½d., a tremendous development could be made in the domestic load. By taking 10 per cent plus ½d., and superimposing that on the rate in use in Glasgow, we find that for the small user—the man with a rental of, say, £35—with a fixed charge of £3 10s. plus ½d., he would be ready to change over to the new system when his consumption reached 900 units per annum. Similarly, consumers occupying houses rented at £40, £60 and £70 per annum would be ready for changing to the new system when their consumptions reached 1 200, 1 400 and 1 700 units respectively, with an average price of 1·49d. per unit. If they adopt the new system and use, say, 3 000 units the average rate for all electricity used is 1·06d. per unit. In Glasgow, we have gone almost as far as any other undertaking in developing the cooking load, and we have now 400 cookers on hire at a rental of £2 per annum, which is less than the 20 per cent figure put forward by the author. Some curves (see Fig. B, page 394) which I have had prepared show the demand from domestic consumers in residential areas in this city. There is one point of difference in the domestic load curves in the paper, as compared with what might be expected in Scotland, in that the author's curves show a considerable load on Sundays. Unfortunately we cannot expect that here.

Mr. E. Seddon: There can be no doubt that we have only touched the fringe of the possible domestic load which can be obtained by a well-organized advertising scheme. Electricity departments should be prepared to hire out apparatus to prospective heating consumers who can make trials of cookers, etc., without incurring much expense to themselves. The gas industry obtained their valuable domestic load from such a scheme. In Edinburgh we have not yet taken any energetic measures to secure this load, but we are now making a move in that direction. It seems to me that it will be unwise to push the use of heavy appliances where new consumers are already using gas, but that we should, in the first case, get the consumers interested in light articles such as grills, irons, etc., which will give them confidence in the use of electric heating apparatus. The development of this load is very much bound up with a suitable tariff. I look forward to the time when a suitable flat-rate charge can be made for all domestic supplies, with a minimum charge per lamp installed ensuring a reasonable revenue from every consumer. I think that domestic consumers with a heating load well established will provide a load factor equal to that of most industrial concerns and can be offered equally good terms. The curves shown by the author are taken from specially equipped houses, and I think that the consumption is higher than one would expect from the average consumer with the same appliances. Nevertheless, the paper indicates the amount of business that can be obtained from the small householder. Finally, although slot meters may be quite suitable for artisan dwellings they cannot be recommended generally.

Mr. R. Hardie: I have to express my entire agreement with the author. Glasgow has been for some time past proceeding generally on the lines laid down, and results indicate that these are sound. We have discovered that there is a vast desirable heating and cooking load awaiting exploitation and obtainable with the minimum of capital expenditure. The electric cooker alone, in use three times a day all the year round, will convert a non-paying lighting consumer into a profitable one, and this without additional expenditure on feeders, mains or service cables. The folly of having domestic services lying inactive for most of the day all the year round (and all day in the summer months) must be recognized. With regard to rates, we in Scotland dare not suggest the author's figure of 8d. per unit for lighting, nor do we approach the 1½d. rate mentioned for cooking. Obviously the cooking rate must be made sufficiently attractive to secure business. In other words, the cooking rate should be fixed at that figure which local experience decides is as high as can be secured for a service that is competitive with coal and gas. In some parts of the country 1½d. may suffice—in others 1d. per unit—while in a few supply areas favoured with large and economical generating units and with adjacent supplies of low-priced coal the ultimate figure may be as low as ½d. I agree with the author's contention that every official, nay every employee, in an electricity supply undertaking should possess knowledge of domestic electrification based on actual use of apparatus in his own house. The advertising value of this would be far reaching. The lack of definite performance data on the cooking load has hindered the proper development of this business, but the information contained in the Billingham curves, presented by the author, and the fact that these are confirmed by the figures obtained in Glasgow and elsewhere, should do something towards removing doubt from the minds of electricity executives, and should encourage them to go forward and acquire a larger share of the domestic business. Another branch of propaganda urged by the author, the "Electric Home" exhibit, is deserving of more general adoption. Its educational value is far reaching, and probably no other form of advertising will do more to bring home to the public the desirability of having their houses adequately wired.

Mr. A. Mears: The lighting and industrial loads have already been acquired in a very large measure by electricity stations, but the heating and cooking load to a large extent represents a new field of development calling for special consideration. In Edinburgh we have been unable to do much to develop this load owing to a shortage of generating plant, but this con-

FIG. B.

Total installation.

(a)

	amps.
173 m.f.* lamps	36
12 radiators	77
5 irons	10
4 vac. cleaners	8
1 cooker	26
	157
50 amp. shunt: max. 20 amps.	

(b)

	amps.
205 m.f. lamps	44
8 radiators	74
2 irons	4
1 kettle	2
	124
50 amp. shunt: max. 8 amps.	

* Metal filament.

Total installation.

(c)

	amps.
288 m.f. lamps in houses	59
17 radiators	136
11 irons	22
2 kettles	5
2 hire cookers	52
	274
50 amp. shunt: max. 32 amps.	

(d)

	amps.
323 m.f. lamps	66
1 cooker	26
13 irons	26
3 radiators	24
2 kettles	5
2 vac. cleaners	[illegible]
	151
50 amp. shunt: max. 13 amps.	

Total installation.

(e)

	amps.
324 m.f. lamps	66
1 cooker	26
1 grill	6
16 irons	32
11 radiators	88
8 vac. cleaners	16
1 kettle	3
	237
50 amp. shunt: max. 32 amps.	

(f)

	amps.
327 m.f. lamps	67
1 cooker	26
13 radiators	104
12 irons	24
6 vac. cleaners	12
2 kettles	6
	239
50 amp. shunt: max. 26 amps.	

Total installation.

(g)

	amps.
108 m.f. lamps in houses	23
9 m.f. lamps in stairs	1·5
4 m.f. lamps in street	1
13 irons	26
3 radiators	28
2 hire cookers	52
	131
50 amp. shunt: max. 14 amps.	

(h)

	amps.
144 m.f. lamps in houses	30
12 m.f. lamps in stairs	2
2 m.f. lamps in street	0·5
14 irons	28
3 radiators	24
6 hire cookers	156
	240
50 amp. shunt: max. 26 amps.	

dition has now disappeared and we find the domestic load increasing rapidly. The latter can, however, only be obtained by fixing a suitable tariff which must be kept as low as possible. It appears to me that simplicity should be the keynote of it, as a tariff that calls for a calculation with each consumer as to the ultimate rate per unit which he will pay for electricity used for heating and cooking is not appreciated. On the basis of simplicity a flat rate per unit for heating and cooking consumptions appeals to the consumer. It is true that this means a separate circuit and meter for the heating and a certain extra expense in wiring, but after all, is the expense so much more than that of a combined lighting and heating installation if the latter is properly arranged, the lights being fused independently of the heaters so as to give proper protection for the lighting? In Edinburgh our charges for lighting and heating are on the flat-rate system and, naturally, separate circuits are required for lighting and heating, but up to the present this has not proved a drawback to the installation of heaters in the larger houses where the heating load is likely to be of reasonable amount. Apart from this question of expense of the extra circuit there is no reason why a flat-rate tariff cannot be arranged to give as cheap result for heating as any other system. It is found that the variation in the annual consumptions for lighting purposes in houses of similar size and character is very considerable, and under most of the two-part tariff rates a consumer who is below the lighting average fails to get the same advantage for his heating rate as one who is much above this average. The simplicity of the separate flat rate for heating undoubtedly appeals to the average consumer, though it may be possible in the future to educate the consumer to some two-part tariff. In Edinburgh the case of the small consumer whose heating appliances are mainly of the lamp-holder variety and whose consumption is so small that it is not worth a separate circuit has been met by charging him an arranged quantity of units for lighting, and all units recorded in excess of this quantity at heating rate. This arranged quantity is based upon past records and general averages, but the method is really an attempt to give him the benefit of two circuits without running the second one. It is the system originated in Glasgow on maximum-demand lines, but adapted to the usual flat-rate method of charge in use in Edinburgh. On the whole it is satisfactory, but, like all systems which depend upon the fixing of a quantity not accurately known, it does not please every consumer. The two-part tariff on the maximum-demand basis, where the demand for lighting only is taken, suffers from the same drawback, as this demand as a rule cannot be known accurately. Apart from the question of tariffs, electric cooking with electric ranges cannot, I fear, advance much without a system of hiring by supply authorities. Not many consumers will experiment owing to the cost of the ranges and the probability of high maintenance costs. The interest which the public take in electrical appliances of all kinds in exhibitions is a very good sign, but there is no doubt that a large amount of educational work remains to be done before the domestic load develops to any great extent. A very interesting figure in connection with this subject is the actual diversity factor of this class of load quite apart from the question of the proportion of the heating load that is included in the lighting peak, i.e. the sum of the maximum demands of the heating consumers divided by the maximum demand made on the station. The author suggests a value of 9 for this figure, but that is surely much too high. This figure is of considerable importance when the question of price per unit is being arranged. The principal feature of the domestic load is the improvement on the annual load factor of the station that it should produce, and on this ground it is to be encouraged as much as possible.

Professor F. G. Baily: One reason for the slowness with which domestic electric appliances are gaining recognition seems to me to be the initial expense. A mere kettle costs some 30s. and a vacuum cleaner £15, and people hesitate to spend this if they have any doubt of its suiting their convenience. Hence I advocate facilities for hiring articles of this kind for a short period. Sales would almost always follow when the consumer had realized the resulting saving in trouble. This is even more important in the case of electric ovens, where the ovens and power circuits will cost £30 to £50 and will involve a complete rearrangement of the kitchen department. A consumer should be able to hire an oven and temporary wiring and switches, which can be installed without disturbing the kitchen range, and when fully satisfied he will proceed to a complete change; but it is demanding much faith in electricity to propose a drastic change in so vital a part of a household as the kitchen. Another point is that of hot water. It is futile to expect electric energy to compete with a properly constructed hot-water boiler, which is a highly efficient apparatus and gives opportunity also for some central heating. An all-electric house may be satisfactory in a warm climate, or in a small flat, where convenience far outweighs expense, but I can only regard it as a fad in an ordinary household in the northern and eastern parts of Great Britain. It must be remembered that while undoubtedly a considerable portion of the heat of the coals in an open grate or kitchen range goes up the chimney, by no means all of it comes out at the top. Much of this escaping heat reappears in the upper rooms and passages, which without this would be chilly and damp. The total heat of electric energy at 2d. per unit costs 40 times as much as that of coal at 40s. per ton, so for straightforward heating there must be very strong reasons for adopting the more expensive agent.

Mr. W. J. Cooper: I cannot understand the attitude of certain business men towards the two-part system of charging. No one knows better than these same business men what on-cost charges are; yet, when an electricity supply authority proposed to charge their product on the basis of an on-cost charge plus a charge per unit used, there was difficulty in getting them to understand and to appreciate the system. We can overcome the objections to a certain extent by expressing the standing charge in banks of units, on the lines of the Glasgow domestic heating tariff.

Mr. A. S. Hampton: Amongst all the suggestions with regard to tariffs I have not heard any in the shape

of a tariff based on a charge of so much per room plus a running charge per unit used. This would only mean one meter, and a very low rate per unit might be reached. Everyone would understand a charge of this kind. There is a difficulty in getting the average householder to see the advantage of two meters or the two-part tariff. I admire the Glasgow Corporation rate; it seems to be very fair and it only requires one meter. It is practically the same as the rate which I have suggested, viz. an annual charge per room, and a very low flat rate per unit. It gets rid of the two-circuit wiring, which is some considerable advantage, and it allows the easy use of the small power appliances.

Mr. A. Ogilvie: The subject is of much importance to public supply companies and, in its development, benefit will accrue to the consumers. The two-tariff system is attractive and fair to the consumer, while it is reasonably remunerative to the supply company. I would, however, leave the main questions raised to those more intimately and directly interested, and confine my few remarks to one feature in the propaganda proposals, namely, what is to be the precise position of the local electrical contractors in connection with the sales and work which it is suggested should be carried out by the public supply undertaking? It is observed on page 201 that the contractor would be properly dealt with in regard to any sales effected and I should like to ask the author if he would indicate (1) How it is proposed to protect the contractor, and (2) how it would be possible to ascertain the contractor responsible for each individual sale effected by the public supply company from their showrooms. Again, it would appear from the remarks on "Showrooms" that it is intended that the public supply company should carry out electrical work in the consumer's premises. If so, then the whole question of municipal trading arises, and while it may at first sight appear to be a side issue on the larger question raised by the paper, still it is a most important one for those ratepayers engaged in the electrical industry generally. (This aspect, of course, applies only to cases where the municipality control and operate the electrical undertaking.) The question of a municipality utilizing ratepayers' money for carrying on a commercial enterprise in direct competition with the ratepayers engaged in that industry, is a large one and one which I venture to think should not be allowed to enter into any propaganda work under domestic-load-building schemes. So long as consumers can obtain their requirements (both labour and material) at reasonable terms from the local contractors—which is almost invariably ensured by local trade competition between contractors—then I suggest that domestic-load-building schemes would, in the end, be best served by the electrical undertaking confining their efforts to demonstrating in their showroom the many and varied uses to which electricity may be put in domestic and industrial fields, leaving the local contractors to supply the consumers' requirements thereafter. The author's views on this point would be interesting.

Mr. D. S. Munro: None can challenge the wisdom of the advice that all those dealing with domestic supply should themselves have practical experience of its working in their own homes. To this may be added the provision of an experimental room at the power station or other showroom where each cooking or other device may be demonstrated by the officials thus trained at home. The author refers to records. There is need for more records available to the whole trade, records of actual facts, not faked for competitive purposes. Some of these would refer to results obtained by trial of this or that appliance as well as to guiding figures obtained by recording group results such as those indicated on page 198 of the paper. The author gives the annual units used per kW installed as 360, and the kW installed as 65. $360 \times 65 = 23\,400$ units. But, a few lines below, he gives that portion which falls on the peak as 5 kW demand and the units on this demand as 3 240. $3\,240 \times 5 = 16\,200$ units. Perhaps I have not understood the figures, but they may possibly be made clearer so that the load factor of this little group of consumers may be ascertained. As regards a two-part method of charging for energy, customers are not fond of it. If it is governed by a demand indicator it tends to restrict use. If it is a fixed kW charge varying with kW installed it makes the consumer reluctant to install lamps of occasional convenience, or to add further appliances—such as a washing machine which is intended only for occasional use. If the fixed charge be calculated from the floor area or the rated valuation of the house it is open to objection on other grounds. Yet some sort of two-part charge is fair and will become necessary. In some cases a low average consumption is predetermined, and all current up to this amount is charged at a high figure per unit, all further units for any purpose being charged at the lowest possible price per unit. This method has several incidental advantages—one meter and one house wiring system, for example—and I should be glad to hear opinions as to the fairest method of arriving at the number of units to be charged at the high rate. One of the objections to a fixed charge arises when a house is empty for a considerable part of the year. The figure in Scotland for sundry units would probably differ widely from that in England, though not so much now as formerly. As a contrast to the methods of a fixed charge per quarter or per kW maximum demand, there are suppliers who not only charge a special rate per unit for cookers and the like but actually present the consumer with something towards the first cost of the appliances which are going to increase his maximum demand. Merely noting the satisfactory point emphasized by the author that this class of individual demand has a comparatively small effect on the whole system peak—though it is easily possible that a small town of big residences might be doing much cooking for dinner at the very time of heaviest lighting demand—I pass on to add a word or two about the sale or rental of appliances by the suppliers of electricity. If this system be necessary to promote output of electricity it might be equally justifiable for the suppliers to rent wiring installations. So I ignore the unfairness of such forms of competition and merely remark that it should pay suppliers well to support around them that large body of influential canvassers represented by the electrical contractors.

Mr. W. A. Gillott (*in reply*): With few exceptions this discussion has been upon similar lines to those at other Centres, and in consequence the replies already given to speakers in those discussions dispose of many of the questions now raised. I therefore propose to confine my reply to the items of special mention.

Mr. Mitchell refers to the suggested fixed charge of £8 10s. causing consumers to hesitate to adopt such a tariff, but this sum would cover a household with 1 kW of lighting installed, and of course is adjusted to suit the capacity of each lighting installation. The rental value of such a household in Glasgow would doubtless be approximately £80, and under Mr. Mitchell's proposed tariff the fixed charge would be similar. It is indeed very encouraging to receive confirmation that Scottish returns of domestic load prove cooking and heating to be practically "off peak" loads to such an extent that it is not necessary to consider them when assessing a fixed charge in the tariff. The load curves of Mr. Mitchell's Fig. B indicate that the demand is approximately 10 per cent of the total installed watts.

Mr. Seddon and Mr. Mears mention the use of small appliances from a lampholder and appear to lean to the view that it is preferable to start a consumer with such devices and gradually lead up to the complete cooker. I have no hesitation in saying that the complete cooker is such a satisfactory proposition that where the supply is offered at 1½d. per unit or less one can with every confidence thoroughly recommend a consumer to install the complete article from the commencement, and I suggest that if the business is handled upon these lines, good results will be secured by all parties concerned.

Mr. Hampton refers to the tariff with its fixed charge based upon the floor area, as in Dundee. A reference to this system is given on page 216.

Mr. Ogilvie asks what is the position of an electrical contractor in a propaganda campaign, and whether the supply authority should carry out the installation work. This subject is such a highly political one that I am afraid it cannot be properly dealt with here, but I would repeat that I firmly believe in the principle of straightforward co-operation, either side not expecting too much from the other, but each working with one object in view, i.e. to give good service to the client. This will result in the establishment of good general conditions between the contractor and the supply authority.

Mr. Munro asks for further details regarding the first set of figures given on page 197. The actual details as to the results obtained under test are given below, and it will be found they are slightly different from those previously given, as only round figures were quoted.

From a study of the returns of 13 consumers it was found that the average kW installed was 5, the maximum being 6 kW and the minimum 3·2 kW. The *average* maximum demand per *individual consumer* was 3 kW. The average units consumed per annum per consumer were 1 800, and the sum of the consumers' maximum demands represents 181 amperes. The maximum result caused by the 13 consumers was 75 amperes, therefore the diversity factor among these 13 consumers is $181/75 = 2\cdot41$.

The amount of resultant load from these 13 consumers that fell upon the system peak was 20 amperes, which occurred at 12 noon, when the system curve was falling. This equals 0·285 of the maximum resultant load, so that the units consumed per kW demand on the system peak are $360 \times 2\cdot41 \times 3\cdot75 = 3\,253$.

The figure of 360 is obtained by dividing the total kW installed into the cooking units consumed by the 13 consumers. From these figures it will be seen that the diversity factor in this instance is $2\cdot41 \times 3\cdot75 = 9$. The figure of 3·75 is the ratio between the 75 amperes resultant demand, and the 20 amperes that fall upon the system peak.

DISCUSSION ON

THE PROPERTIES OF THE DISTRIBUTION FACTOR OF ARMATURE WINDINGS." *

Mr. A. E. Clayton: At the present time considerable importance attaches to the higher harmonics present in alternating E.M.F. and current wave-shapes, and there is reason to expect that importance to increase rather than to diminish. As a result, the values of the distribution factors for these harmonics are of much moment to those interested in the design of alternating-current machinery. Values of these factors for various normal slottings have been tabulated by, amongst others, Dr. S. P. Smith and Mr. R. H. Boulding,† and by Mr. B. Hague.‡ Such tables, although very valuable, are, as stated by the authors on page 865, limited to a few common cases, and are therefore to a certain extent limited in their application. It is thus undoubtedly desirable to have the data available in a simple form suited to perfectly general application, either in the form of tables, or in the form of graphs. The paper is therefore of great interest; to me it is of particular interest as some time since I also was intrigued by the problem of representing these factors in a simple, graphical manner.

The graphs in Fig. 3 indicate clearly the effect of the number of slots per group, q, upon the value of the distribution factor for any particular value of the equivalent angle of spread of the winding, $m\sigma$. From the graphs it is possible to obtain the value of the factor under any given set of conditions. (In this connection, the use of 12 ordinates per range of π is to be deplored. Such a choice is only suited for the quite normal case of three-phase and two-phase windings, i.e. the few common cases mentioned above. The choice of 10 ordinates, or, better still, 18, is more suited to general application.) For practical purposes, however, the authors put forward a series of graphs in Figs. 4 (a) to 4 (d), in which values of the factors for harmonics up to the seventh order are plotted against the angular phase-spread expressed in degrees. These form a valuable set of graphs about 30 in number, but limited to harmonics up to the seventh order.

In developing the mathematics of the subject the authors have expressed their results in terms of the angular spread of the phase group; simpler results are possible if they are expressed in terms of the angular slot-pitch. For example, with q equal vectors displaced by 2γ between successive vectors, it is at once obvious that the numerical value of their resultant will be the same as that when the displacement is $2M\pi \pm 2\gamma$, where M is any integer; this expression is independent of q. If, on the other hand, we deal with the total angle θ between the first and last vectors, for the resultant to have the same numerical value the displacement must be $q \, . \, 2M\pi \pm \theta$, a value which increases directly with q. Thus the distribution factor corresponding to the mth harmonic may be stated in the form utilized by the authors, viz. $(\sin m\sigma/2) \div (q \sin m\sigma/2q)$. Alternatively it may be expressed in the form $(\sin qm\gamma)/(q \sin m\gamma)$. The former expression when plotted as a function of $m\sigma$ gives a graph which, numerically, is periodic with range $2q\pi$. The latter when plotted as a function of $2m\gamma$ gives a graph which for all values of q is periodic, numerically, with range 2π. It thus appears that the best method of tabulating these factors is as functions, not of σ or $m\sigma$, but of the equivalent slot-pitch $2m\gamma$, i.e. of the slot-pitch expressed in electrical measure to correspond to the particular harmonic under investigation. Similarly, it would appear that the best method of plotting out the factors is in terms of the equivalent slot-pitch above mentioned. It then becomes possible, on the same base from 0° to 180°, to plot graphs representing the factors for various values of q, e.g. 2, 3, 4, 5, 6, 8 and 10. From these seven graphs the values of the factors corresponding to any harmonic can at once be read off, for any value of the equivalent slot-pitch. With this common base it is easily possible to deal with angles above 180°, i.e. values of $2m\gamma$ greater than π. All that is necessary is to number each main ordinate with the values of the first four angles to which it corresponds. Thus the 10° ordinate is numbered 10°, 350°, 370°, 710°, etc., the 20° ordinate 20°, 340°, 380° and 700°, etc. It is extremely unlikely that any harmonic for which the equivalent slot-pitch much exceeds 720° will require investigation, as this figure corresponds very closely to the value obtaining for the tooth-ripple harmonics of the second order. The sign of the factor, although often of little importance, is also very simply obtained. When q is an odd number, the sign is always as given by the graph; when q is even, the sign as given by the graph must be reversed for angles lying between 180° and 540°, and, of course, between 900° and 1 080°, etc. The first limits include certainly all the cases that need to be considered, in this respect, in practice.

In a paper on "A Mathematical Development of the Theory of the Magnetomotive Force of Windings," * I have given tables showing the value of the distribution factor for values of the equivalent slot-pitch, $2m\gamma(180°/\pi)$, from 0°, in steps of 2°, to 180°, and for $q = 2$, 3, 4, 5, 6, 8, 10 and 12. These tables cover all the numerical values of the factor for the given values of q. I have also represented the values of the factor in the form of a simple family of graphs on the lines mentioned above. A single graph serves for harmonics of every order for one particular value of q. Thus, for example, with $q = 3$ the distribution factors are read off from a graph representing $\sin \frac{1}{2}(3\theta)/3 \sin \frac{1}{2}\theta$ plotted from $\theta = 0°$ to $\theta = 180°$, the ordinates being numbered as indicated above. If, for example, the slot-pitch were 14°, corresponding to an

* Paper by Messrs. B. Hague and S. Neville (see vol. 60, page 861).

† *Journal I.E.E.*, 1915, vol. 53, p. 205.

‡ *Electrician*, 1917, vol. 78, pp. 710, 740 and 765.

* To be published in a later number of the *Journal*.

unusual slotting, the factor for the fundamental is read off at 14°, for the second at 28°, for the third harmonic at 42°, . . . the 21st at 294°, etc. For $q = 4$ and the same slot-pitch the values of the factor would be read off from a graph representing $\sin \frac{1}{2}(4\theta)/4 \sin \frac{1}{2}\theta$, and it would be necessary to reverse the sign of the factors read off between 180° and 540°. For values of q greater than 12, the winding factors for the lower harmonics approach so closely those for a corresponding surface winding that, in common with the authors, I have found it convenient to utilize the graph representing $\sin \frac{1}{2}\theta/\frac{1}{2}\theta$. For the higher harmonics it is sufficient to remember that when S, the number of slots per pair of poles, is an integer, the distribution factors for harmonics of orders $MS \pm m$ all have the same numerical value as for the mth harmonic. It is desirable, however, to be able to obtain accurately and simply the values of the factors in certain cases. The error of 28 parts in 77 quoted by the authors may occasionally be of moment, although it occurs in a relatively small term. The correct value of the factor can readily be deduced from the above graph, for

$$\frac{\sin qm\gamma}{q \sin m\gamma} = \frac{\sin qm\gamma}{qm\gamma} \cdot \frac{qm\gamma}{q \sin m\gamma}$$
$$= \frac{\sin \frac{1}{2}m\sigma}{\frac{1}{2}m\sigma} \div \frac{\sin m\gamma}{m\gamma}$$

Hence, to obtain the correct value it is only necessary to divide the factor obtaining for a surface winding of spread $m\sigma$ by that obtaining for a spread of $2m\gamma$, i.e. a spread of the equivalent slot-pitch.

For example, with $q = 12$, and 18 slots per pole, the equivalent slot-pitch for the 17th harmonic is 170°, and the equivalent spread of the phase group is $17 \times 120° = 2\,040°$. The factors corresponding to these spreads are, respectively, $0 \cdot 672$ and $-0 \cdot 049$. Hence the actual distribution factor is $-0 \cdot 049/0 \cdot 672$, i.e. $-0 \cdot 073$, instead of the value $-0 \cdot 049$ which obtains for the corresponding surface winding.

Messrs. B. Hague and **S. Neville** (*in reply*): Though the authors think it doubtful whether the results are simpler when expressed in terms of the slot-pitch instead of the phase-spread, yet they welcome the attention which Mr. Clayton has drawn to the former method of representation. The general form of the curves remains, of course, unchanged; and although the complete period is reduced from $2q\pi$ to 2π in all cases, the curves make q oscillations about the axis in that period. In tabulation, apparently there would be little to choose between the two methods; and in plotted curves it becomes a question of whether a longer base-line or a curve crossing the axis at frequent intervals is to be considered the more convenient. From the purely mathematical point of view, it is to be noted that each of the forms in which the distribution can be expressed, namely $(\sin m\sigma/2)/(q \sin m\sigma/2q)$ and $(\sin qm\gamma)/(q \sin m\gamma)$, has its own particular merit; both forms have been used in the papers cited above by Mr. Clayton.

For practical purposes the method adopted in the paper may be preferred. In the alternative method, the curves for different values of q cross and recross each other in a rather bewildering manner; the curves do not remain distinct (as in Fig. 4, for instance), on account of the very different shapes of the several curves. The confusion is greatly increased by each further value of q that is shown. The arrangement of Fig. 3 avoids this difficulty, and shows clearly the change introduced into the curve by each successive increase of q. Mr. Clayton proposes, for practical use, to omit curves for q greater than 12. It is then impossible to find the factor for, say, $q = 13$ or 14 from the set of curves, while in Fig. 3 any higher value of q can be directly dealt with, accurately if α is not greater than 6π, and to a fair approximation for any greater angles, by comparison with the curve for $q = \infty$. This last and important curve cannot be combined with others plotted to a base of slot-pitch.

The authors wish to express their great indebtedness to Mr. Clayton for his simple formula for deriving the distribution factor for any slotting from the curve for a uniformly-distributed or surface winding. Expressed in the notation of the paper, Mr. Clayton's formula becomes

$$f_q(\theta) = f'(\theta) \div f'(\theta/q)$$

that is, the distribution factor for q vectors spread over a total arc of 2θ is equal to that of an infinite number of vectors occupying the same total arc divided by that of an infinite number of vectors occupying the space between any pair of the actual vectors. By this simple operation the range of Fig. 3 is extended indefinitely and without approximation, thus covering the only region for which accurate values are not directly indicated in the curves reproduced. Applying the rule to the example mentioned in the footnote on page 864, from the curve in Fig. 3 the distribution factor at α/q (that is, $\pi/2$) is found to be $0 \cdot 635$; the value at α (that is, $13\pi/2$) is $0 \cdot 049$; so that the correct value for $q = 13$ is $0 \cdot 049/0 \cdot 635 = 0 \cdot 077$.

ANNUAL DINNER, 1923.

The Annual Dinner of the Institution was held on Tuesday, 6th February, 1923, at the Hotel Cecil

The President, Mr Frank Gill, presided over a gathering numbering about 480 persons. Among those present were: The Rt. Hon. Neville Chamberlain, M.P. (*Postmaster-General*), Sir W. Joynson-Hicks, Bart., M.P. (*Parliamentary Secretary, Overseas Trade Department*), The Rt. Hon. Lord Southborough, P.C., G.C.B., G.C.M.G., G.C.V.O. (*Honorary Member*), The Rt. Hon. Lord Askwith, K.C.B. (*Chairman of Council, Royal Society of Arts*), The Rt. Rev. Bishop H. E. Ryle, K.C.V.O. (*Dean of Westminster*), Sir Anthony Bowlby, K.C.B., K.C.M.G., K.C.V.O. (*President, Royal College of Surgeons*), Sir S. Chapman, K.C.B., C.B.E. (*Permanent Secretary, Board of Trade*), Sir R. T. Glazebrook, K.C.B., F.R.S. (*Past President*), Sir Frank Heath, K.C.B. (*Secretary, Department of Scientific and Industrial Research*), Sir Evelyn Murray, K.C.B. (*Secretary, General Post Office*), The Hon. Sir T. H. Holland, K.C.S.I., K.C.I.E., F.R.S. (*Rector, Imperial College of Science and Technology*), Sir John Cadman, K.C.M.G., D.Sc. (*President, Institution of Mining Engineers*), Major-Gen. Sir William Liddell, K.C.M.G., C.B., late R.E. (*Director of Fortifications and Works, War Office*), Sir Westcott Abell, K.B.E. (*Chief Ship Surveyor, Lloyd's Register of Shipping*), Sir Arthur Colefax, K.B.E., K.C., Sir James Devonshire, K.B.E. (*Honorary Treasurer*), Sir William Hale-White, K.B.E., M.D. (*President, Royal Society of Medicine*), Sir Joseph Petavel, K.B.E., D.Sc., F.R.S. (*Director, National Physical Laboratory*), Sir Robert Robertson, K.B.E. (*President, Faraday Society*), Sir A. I. Durrant, C.B.E., M.V.O. (*H.M. Office of Works*), Sir William Noble (*Member of Council*), C. T. Allan (*Joint Hon. Secretary, Western Centre*), Ll. B. Atkinson (*Past President*), F. G. C. Baldwin (*Chairman, North-Eastern Centre*), W. N. Bancroft (*President, Chartered Institute of Secretaries*), J. W. Beauchamp (*Member of Council*), W. E. Burnand (*Past Chairman, North Midland Centre*), Alfred Carpmael, A. C. Chapman, F.R.S. (*President, Institute of Chemistry*), R. A. Chattock (*Member of Council*), F. W. Crawter (*Member of Council*), R. A. Dalzell, C.B.E. (*Director of Posts and Telephones, General Post Office*), W. R. Davies, C.B. (*Principal Asst. Secretary, Technical Branch, Board of Education*), D. N. Dunlop (*Member of Council*), Dr. W. H. Eccles, F.R.S. (*Vice-President*), K. Edgcumbe (*Member of Council*), A. S. Hampton (*Chairman, Scottish Centre*), A. F. Harmer (*Member of Council*), Dr. H. S. Hele-Shaw, LL.D., F.R.S. (*President, Institution of Mechanical Engineers*), J. S. Highfield (*Past President*), Captain H. Hooper (*Hon. Secretary, South Midland Centre*), G. W. Humphreys, C.B.E. (*Chief Engineer, London County Council*), Dr. R. Knox (*President, Electrotherapeutic Section of Royal Society of Medicine*), Lieut.-Col. F. A. C. Leigh, T.D., R.E. (*Member of Council*), W. M. Mordey (*Past President*), A. Page (*Member of Council*), C. C. Paterson, O.B.E. (*Vice-President*), A. C. Peake (*President, Incorporated Law Society*), Major T. F. Purves, O.B.E. (*Engineer-in-Chief, General Post Office*), Councillor E. C. Ransome (*President, British Electrical Development Association*), W. R. Rawlings (*Member of Council*), P. F. Rowell (*Secretary*), Dr. A. Russell (*Member of Council I.E.E., and President, Physical Society of London*), A. M. Sillar (*Chairman, Association of Consulting Engineers*), Roger T. Smith (*Past President*), C. P. Sparks, C.B.E. (*Past President*), S. J. Speak (*President, Institution of Mining and Metallurgy*), A. A. C. Swinton, F.R.S. (*Vice-President*), H. L. Symonds (*Chairman of Council, London Chamber of Commerce*), F. Tremain (*Chairman, Western Centre*), C. Vernier (*Member of Council*), E. B. Vignoles (*Chairman, British Electrical and Allied Industries Research Association*), C. H. Wordingham, C.B.E. (*Past President*).

After the usual loyal toasts, the President read the following message:

"His Royal Highness the Prince of Wales had hoped till the last moment to be able to give his favourable consideration to the President and Council's invitation to be present at the Annual Dinner of the Institution, but the overwhelming number of invitations which he has received for 1923 (the majority of which are of long-standing, having accumulated during his various absences overseas) has rendered the drafting of his programme for this year of unusual difficulty. The Prince fears that as a result he will be unable to accept the Institution's kind invitation for 1923, though there is of course nothing to prevent the Council, should they so desire, from renewing it on some future occasion when His Royal Highness is in England."

The President also read the following messages which had veen received from other societies:

From French Society of Electricians.

"The French Society of Electricians sends most cordial greetings to the President and members of the Institution of Electrical Engineers on the occasion of the Annual Dinner. The Society strongly desires the continuance of the most friendly relations between the two bodies and the two nations."—BRILLOUIN, *President.*

From Italian Electrotechnical Association.

"The Italian Electrotechnical Association fully appreciate your kind thought and would ask you to present to their English colleagues the hearty wishes and greetings of Italian electrical engineers. Personally I send you and your Institution my wishes for a happy year and prosperity."—DEL BUONO, *General President.*

From American Institute of Electrical Engineers.

"Please convey to President Gill members of Council and of Institution of Electrical Engineers on occasion their Annual Banquet hearty felicitations from officers and members of the American Institute of Electrical Engineers."—F. B. JEWETT, *President.*

Sir W. Joynson-Hicks, Bart., D.L., M.P. (Parliamentary Secretary, Overseas Trade Department), in proposing the toast of "The Institution of Electrical Engineers," said: In proposing this toast, coupled with the name of your President, I should like to congratulate him on his accession to this high and distinguished position. I am certain that he will fill it in accordance with the great tradition of the past, and that he will be a worthy successor to those great men, such as Siemens, Crookes, Preece, and Glazebrook, who have been your Presidents in times past. Your Institution is one of the marvels of modern days. Beginning some 50 years ago with a very few members, it is now the largest scientific Institution in the British Empire, with a membership of nearly 11 000—a great record and a great Institution. I suppose the reason why the Institution has become so important is partly because of the importance of the electrical agencies and of the electrical profession, and also because of its fundamental principle, which, I understand, is that of advancing knowledge and improving practice—a motto which most Government Departments might well take for their own. May I say that, in carrying out your principle, you might combine with the Government institutions—you doing the research part, and, at all events, the Department over which I have the honour to preside doing the commercial part. I presume that it is because of my official position that I have been asked to propose to-night the health of your Institution, the development of which would assist very greatly in the development of our overseas trade. I want to see research and commerce combined. I am convinced that the commercial man who sneers at research, and who is not prepared to lay out the necessary funds for the development of the industry with which he is connected, is far behind the times and is a hindrance to the progress of commerce in this country and to the development of overseas trade. On the other hand, the pure scientist sometimes works merely for the sake of working, and for the pleasure of investigating the unknown, very often not knowing when he is done. I may say that to-night I have asked, with an inquiring mind, of two of the greatest authorities on the subject, "What is electricity?" and both those scientists have replied that they do not know. But it is by the development of science by the pure scientist, yoked in double harness with the commercial man, that the trade of our country has developed in the past and will develop in the future. I should like to comment on one project which I notice in your Council's last Annual Report, that is, the development of the system of instruction given to overseas students coming here into our factories, our workshops and our training colleges. Remember this—that every student from abroad who comes here, who learns here, and who is well treated here, when he goes back to his own country is worth any ten commercial travellers in the world. He goes back with the determination in his mind that English science, English trade and English manufacture are better than any other science, trade and manufacture in the world. When he gets back to his own country, we may be certain that he will spread abroad the knowledge of English science and English manufacture better than any other agency which the scientists or the manufacturers in this country could devise. I want therefore to see this system very much enlarged and very much encouraged, and if my Department's agencies overseas and its staff here can be of any assistance in bringing together would-be students from overseas and the factories here, we are absolutely at your disposal. May I ask you one more thing? As one who has some knowledge now of our export trade, I say that it is of the very greatest importance that you should continue to standardize in every possible way your electrical specifications so that all the world may realize what those specifications mean, and so that, when the world sees an English specification, it will know it to be one of the best. Whatever difficulties there may be in the trade of the future, whether they are from tariffs or from any other cause, I assure you that quality, for which in the past Great Britain has been famous, will overcome all tariffs and all other obstacles to trade throughout the world. In every country there is always a market for the best. England has always been proud of providing the best. Your Institution has striven in the electrical industry to be of assistance in providing the best. Great as has been your past, great as have been the achievements in electrical science, that is nothing compared with the possibilities of the future. The prospects to-day are even more brilliant than they were 50 years ago. There is no man, however keen a scientist he may be, sitting at this table who would venture to set a limit to the possibilities of the extension of the electrical industry and of electrical discovery. It may be that in another 50 years' time, when some other Ministry of the Crown comes to propose this toast at an enormously enlarged gathering, somebody may be able to answer that question which I asked a few minutes ago. But if it cannot even then be answered, you and I are convinced that although you may not be able to define it in so many words you will define it by the progress of your Institution and by the progress and development of electrical Institutions throughout the world. I give you, with very great pleasure, the toast of "The Institution of Electrical Engineers," coupled with the name of your President, to whom I wish long life and prosperity.

The President, in responding, said: "I have to thank Sir William Joynson-Hicks very cordially for the way in which he has spoken of the Institution, and I am sure that the words which he has used have fallen very gratefully on the ears of those who are enthusiastic about the Institution. To-night I want to talk about three important things. The Report for the year ending March 1922, lately issued by the Electricity Commission, shows that from 536 generating stations the total output for 1921–22 decreased by $5\frac{1}{2}$ per cent. Of those stations, no less than 43 per cent had an output of under one million units per annum. The estimates for eight areas provisionally delimited by the Commissioners show that during the next five years the increase in output will be of the order of 97 per cent, and for ten years about 192 per cent. The published figures, so far as I have seen them, suggest that the estimates will be exceeded. That seems to me to be very hopeful. The reason I mention this is that in this country, owing

to reasons into which it is unnecessary for me to go, we have a considerable number of small undertakings and, although I am not a power engineer, I am sure that the generation business of those small undertakings cannot in many cases be economical. Now, when we consider some of the large undertakings which are at present in operation in Switzerland, on our North-East Coast, in the United States, and in Canada, we can only hope that we shall find in this country a tendency to merge and unify the generation of electricity. Let me give an illustration. Last summer, at Niagara, I went over the Ontario Power Commission's works. The Commission was then supplying 275 municipalities. Its load was equal to about 340 000 h.p. The 1920 price for energy for commercial purposes varied from 1·3 to 5 cents per kilowatt-hour, and for domestic purposes the price varied from 2·2 to 4 cents per kilowatt-hour. Its big power station on the Niagara River was being built with an ultimate capacity of 500,000 h.p. I want to conclude my remarks on this matter with a plea that those who have to deal with these problems in this country will do their best to merge their interests, to amalgamate as far as they can, and to build up big businesses, because it is only big businesses that can be strong. The second big thing I want to refer to is international telephony in Europe. At the first meeting of the Institution this session reference was made to this matter. It was shown that there is no longer any technical difficulty in speaking overland over any distance that may be desired. Since then, on 15th January, it was proved that it was quite possible to speak over long distances over sea. It was shown at our opening meeting that there are working in the world telephone lines in everyday use which appear very long to European eyes—much longer than those we have in practice. I think it is fair to say that no Government in Europe—this is largely a question for Governments—dare take an order for an international telephone call on a contractual basis. It will take the order and do its best, but it dare not take it on a contractual basis because no Government has the control which is necessary. I think it was shown, also, that a first-class extensive telephone service in Europe is not possible under the present conditions. This is no one's fault. The necessary technical advances have only recently been achieved which enable this to be contemplated. At the present time it is no one's job. Since November some progress has been made because the French Government has issued invitations for a meeting, which will probably be held next month, to consider this matter and see what can be done. This is not a matter for co-ordination. It is not a matter for a book of rules. There is only one way to tackle it and that is to deal with it boldly by arranging for unity of control for the whole of the through-business. Sir William has referred to the question of research. I should like to quote from a speech made by Mr. Theodore N. Vail—probably the man who was responsible for more expenditure on research than any other individual in the world's history. Mr. Vail said: "Given the ideas and the knowledge and the brains, development in any line of art, science or industry is largely a question of money." That is very true. Research is costly in the first instance, but it is very profitable in the end. It is, however, becoming more and more a question of organization and team work. I think it is only the big concerns which can afford to spend the money necessary to bring research to successful fruition. That is why I couple these two big things with research. The third big thing I want to mention is the Institution. The membership is now 10 600. During the last four years it has increased by over 3 000. That is at the rate of 9 per cent per annum, a rate which doubles the total in 8 years. The Students' Sections are in a highly flourishing condition. They never were better, and I am glad to say that among those Students are many of those whom Sir William has in mind. There are at present 12 Local Centres or Sub-Centres holding their meetings away from London, and in those Local Centres and Sub-Centres there are 4 700 members, nearly 45 per cent of the whole membership. That is to say, the Institution is able to cater for 45 per cent of its membership away from London. One of those Sub-Centres, Liverpool, has just been granted the status of a Local Centre, with the consent and approval of its late parent Centre. In those Centres splendid work is being and has been done, and I should not like to sit down without expressing the thanks of the Council to the Committees and the Local Officers of those Centres. At the same time I should also like to thank the headquarters staff and particularly the Secretary, Mr. Rowell. I want now to refer to one of the offshoots of the Institution. Twenty-five years ago the late Dr. John Hopkinson, then President, started the Corps of London Electrical Engineers. That body has now been, shall I say, re-galvanized after a period of calm, and it now emerges as the 11th Anti-Aircraft Battalion. Lieut.-Col. Edgcumbe wants recruits and will be very glad of anyone who will come forward. The Headquarters are still at Regency-street, Westminster.

"I have talked about the Institution, but I do not desire to see you occupied solely with the Institution. That would be class interest. The smallest unit that ought to satisfy the members is the nation. We are only part of a body of men who are doing similar or analagous work to ours; the representatives of some of those other societies have honoured us by their presence to-night. To those other societies we are brothers, not rivals. We feel with them the same desire to do service, and we reach forward with them to do our utmost to minister to human needs, and, by applying the gifts which science gives, to do something to render mankind more useful, more happy and more contented. I thank you for the way in which this toast has been received."

Mr. J. S. Highfield, Past President, then proposed the toast of "Our Guests," to which the **Rt. Hon. Neville Chamberlain, M.P.** (Postmaster-General), and **Sir Arthur Colefax, K.B.E., K.C.**, responded.

A reunion was then held in the Victoria Hall of the Hotel.

PROCEEDINGS OF THE INSTITUTION.

688TH ORDINARY MEETING, 30 NOVEMBER, 1922.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 16th November, 1922, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read, and was ordered to be suspended in the Hall.

The following list of donations was taken as read, and the thanks of the meeting were accorded to the donors:—

Museum : The Lords Commissioners of the Admiralty; The Delegacy of the City and Guilds (Engineering) College; The Engineer-in-Chief, G.P.O.; The Committee of the Liverpool Public Libraries; Professor T. Mather, F.R.S.; C. Owen Silvers; The Elder Brethren, Trinity House.

A paper by Mr. W. A. Gillott, Associate Member, entitled "Domestic Load Building: a Few Suggestions upon Propaganda Work" (see page 197), was read and discussed, and the meeting terminated at 8 p.m.

25TH MEETING OF THE WIRELESS SECTION, 6 DECEMBER, 1922.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., took the chair at 6 p.m. in the unavoidable absence of Professor G. W. O. Howe, Chairman of the Section.

The minutes of the meeting of the Wireless Section held on the 8th November, 1922, were taken as read and were confirmed and signed.

A paper by Mr. E. B. Moullin, M.A., entitled "A Direct-reading Thermionic Voltmeter, and Its Applications" (see page 295), was read and discussed, and the meeting terminated at 7.20 p.m.

689TH ORDINARY MEETING, 7 DECEMBER, 1922.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 30th November, 1922, were taken as read and were confirmed and signed.

The President : Before we begin the regular business it is my pleasant duty to present to you our latest Honorary Member, Dr. Fleming.

Dr. J. A. Fleming : I should like to express my deep sense of the honour which the Institution has done me by placing my name on its list of Honorary Members. It is a very high distinction, and one which I value and appreciate very much indeed. I have been a Member of this Institution now for rather more than 40 years, having been elected in the spring of 1882, when I first came to London as a scientific adviser to the old Edison Electric Lighting Company. Looking back on those 40 years I see a wonderful vista of inventions, in the origination and development of which members of this Institution have played a most important part. In those days the name of the Institution was the Society of Telegraph Engineers and Electricians, and there was no "heavy" electrical engineering in the sense in which we now understand the term. The incandescent lamp had only just been invented by Edison and Swan. Dynamo machines in those days were considered rather wonderful if they could run for 24 hours without breaking down. Transformers and alternators had hardly been invented at all, and all our modern appliances, such as wireless telegraphy, were undreamed of. In looking back on that period one sees the first developments of electrical engineering, and I feel confident that in another equal span of time other wonderful inventions will be evolved. Let us hope that if our statesmen and politicians can steer the ship of State into smooth waters, and those conditions return which will give a proper financial reward to all electrical engineers in return for the great benefits which they bestow upon the community, these things will come to pass. It is a distinction to belong to this Institution in any form or in any rank, and it is a very great distinction to be numbered among its Honorary Members.

A paper by Mr. A. M. Taylor, Member, entitled "The Possibilities of Transmission by Underground Cables at 100 000/150 000 Volts" (see page 220), was read and discussed, and the meeting terminated at 8 p.m.

690TH ORDINARY MEETING, 14 DECEMBER, 1922.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 7th December, 1922, were taken as read and were confirmed and signed.

The President: There is a purely formal matter in connection with the Wilde Benevolent Fund which I wish to put to the members. The Council have taken steps for the transfer to the members of the chartered Institution of the benefits under the Wilde Benevolent Fund which accrued to the members of the old Institution. For certain legal reasons the transfer will have to be effected by means of an application to the High Court. As it is possible that the learned judge may ask whether there is a sufficient number in favour of the transfer being effected (there has to be no particular number of members) it was thought wise to ask whether anybody present has any objection. The point is purely formal. I take it that you agree to this course being followed. [The members present unanimously signified their assent.]

A paper by Major J. Caldwell, entitled "Electric Arc Welding Apparatus and Equipment" (see page 253), was read and discussed, and the meeting terminated at 7.45 p.m.

691ST ORDINARY MEETING, 4 JANUARY, 1923.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., President, took the chair at 6 p.m.

The following vote of condolence with the family of the late Sir John Gavey, C.B., Past President, was passed, the members standing in silence:—

"The members of the Institution of Electrical Engineers have learned with profound regret of the death of Sir John Gavey, C.B., Past President of the Institution, and hereby desire to express their sincere sympathy with the members of his family in the great loss which they have sustained through his death."

The minutes of the Ordinary Meeting of the 14th December, 1922, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Mr. F. Creedy, Associate Member, then delivered a lecture entitled "Variable-speed Alternating-current Motors without Commutators" (see page 309), and the lecture was followed by a discussion (see page 326).

The meeting terminated at 8.5 p.m.

26TH MEETING OF THE WIRELESS SECTION, 10 JANUARY, 1923.

(Held in the Institution Lecture Theatre.)

Prof. G. W. O. Howe, D.Sc., Chairman, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 6th December, 1922, were taken as read and were confirmed and signed.

A paper by Mr. C. F. Elwell, Member, entitled "The Design of Radio Towers and Masts: Wind-Pressure Assumptions" (see page 407), was read and discussed, and the meeting terminated at 7.15 p.m.

STATIONARY WAVES ON OPEN-ENDED SOLENOIDS.*

By A. PRESS, Member.

(*Paper first received 6th December, 1921, and in final form 11th April, 1922.*)

The problem of the coupling coil has received new importance physically because of its application to wireless signalling. The nodal-point distribution on an elongated Tesla coil has been recently investigated, and it was found that the nodal distances fell off in value as the ends of the coil were approached.†

This attenuation of distance had been attributed to end-effects, but it will be shown in this paper that the cause is rather a body effect. Naturally, with the maximum self-induction and capacity per unit of length occurring at the middle of the coil, the results must be of altogether different character from those obtaining in a Bessel's antenna,‡ where the capacity per unit of length diminishes as the self-induction coefficient increases. The same would be equally true against the Bessel's cable of Oliver Heaviside,§ although the general differential characteristics still apply.

For the present case assume the following relationship for a coil with the co-ordinate x measured from the centre outward.

$$\left.\begin{aligned} L_x &= \frac{L}{\phi(x)} \\ C_x &= \frac{C}{\phi(x)} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

In the above equations L_x and C_x diminish together towards the ends of the coil, the arbitrary function $\phi(x)$ depending on the geometry of the coil only. In the Maxwellian theory the capacity per unit of length is to be determined from the direct-current condition only with one-half of the coil charged plus and the other half minus. This method has always been implied in dealing with waves along wires (see, notably, the work of Heaviside ||).

The differential equations of condition, neglecting resistance, being of the form ||

$$\left.\begin{aligned} L_x \frac{di}{dt} &= -\frac{de}{dx} \\ C_x \frac{de}{dt} &= -\frac{di}{dx} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

On separating out the voltage and current functions we have

$$\left.\begin{aligned} \frac{d^2e}{dx^2} + L_x \frac{d}{dx}\left(\frac{1}{L_x}\right) \cdot \frac{de}{dx} &= L_x C_x \frac{d^2e}{dt^2} \\ \frac{d^2i}{dx^2} + C_x \frac{d}{dx}\left(\frac{1}{C_x}\right) \cdot \frac{di}{dx} &= L_x C_x \frac{d^2i}{dt^2} \end{aligned}\right\} \quad . \quad . \quad (3)$$

The above equations bear a considerable resemblance to Bessel's equation. If then we make use of equation (1) it follows that for sustained oscillations of frequency $f = (1/2\pi)p$, Equation (3) reduces to

$$\frac{d^2e}{dx^2} + \frac{1}{\phi(x)} \cdot \frac{d}{dx}\phi(x) \cdot \frac{de}{dx} + \frac{LCp^2}{(\phi x)^2} e = 0 \quad . \quad . \quad (4)$$

with a similar equation in i.

The solution of Equation (4) has been determined by the author to be of the form

$$e = [A \sin f(x) + B \cos f(x)] \sin pt \quad . \quad . \quad (5)$$

where we also have as conditions first that

$$\frac{d}{dx} f(x) = \frac{1}{\phi(x)} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and secondly, that

$$f = \frac{1}{2\pi\sqrt{(LC)}} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Provided, therefore, that any function such as $\phi(x)$ is known, the corresponding solution (5) is also known.

By inspection it follows from Equation (5) that the nodal distances of potential and current should progressively diminish toward the free end of the coil. Condition (7) implies that, provided the distributed inductance and capacitance accord with Equations (1), very sharp resonance will result.

To check the above type of solution (5) consider

$$e = A \sin f(x) + B \cos f(x)$$

then $\quad de/dx = A \cos f(x) \,.\, f'x - B \sin f(x) \,.\, f'x$

and $\quad (1/f'x) de/dx = A \cos f(x) - B \sin f(x)$

Operating once more with d/dx we have

$$\frac{1}{f'x} \cdot \frac{d^2e}{dx^2} + \frac{d}{dx}\left(\frac{1}{f'x}\right) \cdot \frac{de}{dx}$$
$$= -A \sin f(x) \,.\, f'x - B \cos f(x) \,.\, f'x = -f'x \,.\, e$$

from which we have, on multiplying through by $f'x$,

$$\frac{d^2e}{dx^2} + (f'x)\frac{d}{dx}\left(\frac{1}{f'x}\right) \cdot \frac{de}{dx} + (f'x)^2 e = 0$$

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† Prof. J. S. TOWNSEND: "Electric Oscillations in Straight Wires and Solenoids," *Journal I.E.E.*, 1921, vol. 59, p. 771; also *Philosophical Magazine*, 1920, vol. 42, p. 248.

‡ A. PRESS: "The Vertical Grounded Antenna as a Generalized Bessel's Antenna," *Proceedings of the Institute of Radio Engineers*, 1918, vol. 6, p. 317.

§ O. HEAVISIDE: "Electromagnetic Theory," vol. 2, p. 238.

|| *Loc. cit.*, p. 239, Equations (1) and (2).

This therefore necessitates, according to the first equation of (3),

$$f'x = L_x \,;\ (f'x)^2 = L_x C_x p^2$$

Writing therefore

$$L_x = \partial/dx(fx) = L/\phi(x) \text{ (where } L \text{ is a constant)},$$

$$C_x = C/\phi(x) \text{ (where } C \text{ is a constant)},$$

we have $L_x C_x = LC/(\phi x)^2 \,;\ L_x C_x p^2 = 1/(\phi x)^2$

provided we put $LCp^2 = 1$, which gives $p = 1/\sqrt{(LC)}$.

Equation (5) may be said to give the "resonant" solution. The "dissonant" solution is given by an expression of the type

$$e = A \sum \frac{1}{n^2} \,.\, \sin nf(x) \,.\, \sin pt \quad . \quad . \quad . \quad (8)$$

which applies more particularly for the case of dead-ends which naturally give rise to out-of-phase reflection phenomena. The latter circumstance has important practical consequences for wireless work where the sharpest type of resonance is a desideratum.

In passing, dealing with the subject of the self-induction coefficient of a coil, it has been held recently that the coefficient is a function of the frequency. There is no evidence of this in Heaviside's "Electromagnetic Theory." Thus in considering a closed circuit we have the expression, neglecting resistance, that

$$n \frac{d\phi}{dt} = e \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where e is the impressed E.M.F. and ϕ represents the aggregate flux linking the circuit, on the basis of n effective turns. Turning now to the case of a very long transmission line [where capacities are naturally present and we have the formula $C = 1/(Lc^2)$, where c is the velocity of light] with a frequency of practically zero value, it is endeavoured to put Equation (9) into the form

$$n \frac{d\phi}{dt} = L \frac{di}{dt} = e \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Here L is presumed to refer to the conductive length of the circuit only. Each elemental length ds of the conductive portion is presumed to add its quota of flux linkages that physically cut the circuit forming the conductor, in accordance with the Faraday requirement. Having thus allocated a definite flux-cutting value to each portion of the conductive part of the circuit for the same current intensity i passing through it, it is further held that for the case of high frequencies, where the current intensity may be varied, the voltage set up per element of length ds is still of the form

$$de = (Lds)di/dt \quad . \quad . \quad . \quad . \quad (11)$$

All the older writers have employed the above theory in their investigations of stationary waves on wires. The method applies, of course, to the electrical configuration coefficient C as well as to the magnetic configuration constant L.

THE DESIGN OF RADIO TOWERS AND MASTS: WIND-PRESSURE ASSUMPTIONS.

By C. F. Elwell, Member.

(*Paper first received* 30*th November, and in final form* 7*th December*, 1922; *read before the* Wireless Section 10*th January*, 1923.)

Summary.

In all theory, design and specifications, some assumptions are necessary and, as experience is gained, the value and accuracy of these assumptions is made apparent. The ultimate weight and cost of a structure is influenced in no small degree by the initial considerations, and in the particular field under review the question of maximum wind pressures and the law connecting such pressures with height above ground level, are of primary importance. It is the intention of this paper to review briefly the results of past experiments and endeavour to point out what are safe and economic values of wind pressures for design purposes. The need for the standardization of wind-pressure assumptions will also be brought out and it is sincerely hoped that practical action will be taken in the near future.

Newton's Theory for Fluids.

The general theoretical treatment extends from the time of Galileo (1590) and was put into practical form by Newton in his "Principia" about 1687 in terms which are expressed to-day by the general formula *

$$p = da\,H = da\frac{v^2}{2g}$$

where p = pressure on the body;
a = area of body;
d = density of fluid;
v = velocity of fluid relative to the plate; and
$H = v^2/2g$ = height required for a body to attain a velocity v under the action of gravity.

This formula modified to apply particularly to air becomes

$$p = \frac{0\cdot0027}{1 + 0\cdot003665t}\cdot\frac{P}{P_1}v^2$$

where p = pressure in lb. per sq. ft. of exposed area;
t = temperature in degrees C.;
P = barometric pressure at place of observation;
P_1 = barometric pressure at sea level at the 45th parallel of latitude and at 0° C.; and
v = velocity of fluid in miles per hour.

At zero temperature and sea-level barometric pressure at the 45th parallel this formula reduces to:

$$p = K \times 0\cdot0027v^2$$
$$= K \times \frac{1}{370} \times v^2$$

* *Engineering News Record*, 1895, vol. 35, p. 175.

In this formula K (equal to 1 in this case) is a constant introduced for the comparison of Newton's theoretical formula with the later formulæ of practice and experiment.

All investigators have sought to prove the formula or to find the extent of the discrepancy, and have found that K varies between 1·3 and 1·8, the gain being ascribed particularly to the partial vacuum in the rear of the plates. In these investigations some have added constants to allow for this, while others have added terms to express variations in the higher powers of v, producing formulæ of the general form

$$p = A + Bv + Cv^2 + Dv^3$$

Examples of formulæ.—Stevenson* gave

$$V = v\sqrt{\left(\frac{H + 72}{h + 72}\right)}$$

where V = velocity at level H; and
h = known height at which the velocity is v.

E. Douglas Archibald † found, from observations between 300 and 1 300 ft.,

$$\frac{V}{v} = \left(\frac{H}{h}\right)^{\frac{1}{4}}$$

where V, v, H, and h are the velocities and heights of the upper and lower instruments respectively. He says "the general and obvious conclusion to be drawn . . . is that the velocity of the wind *always* increases from the surface of the ground up to 1 800 ft. . . ."

Sir Napier Shaw gives‡

$$V = \frac{H + a}{a}\cdot V_0$$

where V = velocity at a height H above ground;
V_0 = observed anemometer reading in a fixed position; and
a = a constant obviously depending on the position of the anemometer, topography and other factors.

In general it has been found that near the earth the actual velocity is exceedingly irregular, but that the *average velocity* increases with height. The rate of increase *increases* with the average velocity, and *decreases* with the elevation.

* *Journal of the Scottish Meteorological Society*, 1880, vol. 5 p. 384.
† *Nature*, 1886, vol. 33, p. 593.
‡ Advisory Committee for Aeronautics Report No. 9, 1909, p. 8.

Among the most interesting observations on the relation of wind velocity to altitude are those of Dr. Cesare Fabris * based on some 200 pilot-balloon flights made at nearly equal intervals during the period June 1910 to May 1911 at Vigga di Valle, Italy, the principal ærological station of the Royal Italian Oceanographic Committee. This station is about 25 miles N.W. of Rome and its co-ordinates are as follows: Lat. 42 04′ 41″ N.; long. 12 12′ 43″ E.; altitude 272·4 m. Fig. 1 † gives an indication of the relative velocity at various heights above ground level, i.e. 272 m. Although the curves are for elevations greatly in excess of those of any interest to the designer of radio masts, it is interesting to note that each shows a distinct and regular increase of wind velocity with height, for the range of 272 m to 600 m, i.e. a range of about 1 000 ft.

J. S. Dines also carried out balloon observations at Farnborough in 1912.

Some Assumptions and Experiments which have been made in the Past.

Tay Bridge Commission.—After the disaster to the Tay Bridge, the Commission gave their finding and rules, of which the following are the most important recommendations:—

Wind pressure to be 56 lb. per sq. ft. on girders, trains, etc., on the actual area exposed to wind, plus an allowance of 28, 42, or 56 lb. per sq. ft. according to whether the ratios of the open spaces of the leeward girders to the total area of the outline of the girder are less than $\frac{2}{3}$, from $\frac{2}{3}$ to $\frac{1}{3}$, or greater than $\frac{1}{3}$.

The same Committee also gave it as their opinion that

$$p = \frac{v^2}{100}$$

The American Society of Civil Engineers, 1880.—Messrs. Welch, Shaler Smith and Collingwood read a paper and gave the following records of the most violent wind force during tornadoes, etc.:—

Blowing down 3 bridges at 18–27 lb. per sq. ft.
Train derailments at 30·5 lb. per sq. ft.
Destruction of brick houses at 58–84 lb. per sq. ft.
Overturning a barrel of tar at 52 lb. per sq. ft.
Overturning a locomotive at 93 lb. per sq. ft.

They mention the case of a piano being lifted bodily, transported 270 ft. and set down again on its legs without apparent injury.

Ingberg † in 1917, writing of the effects of tornadoes in recent storms, gave the figures, calculated from the damage done, of 27, 31, 37, 29, 45, 39 and 20 lb. per sq. ft. He says: "These pressures (tornadoes) are rarely in excess of 60 lb. per sq. ft., so that structures designed for a load of 30 lb. per sq. ft. with a factor of safety of 2 or more come through intact as to their main structural members."

Tests made on the Forth Bridge by Sir Benjamin Baker (1884–1890).‡—In the years mentioned 14 gales were experienced. Records of two were rejected on account of suspected inaccuracy of the instruments. For these tests the following methods of measurement were adopted: A large fixed board or gauge 20 ft. by 15 ft. was erected on top of the old castle on the island of Inch-Garvie, placed so as to be parallel with the bridge, and provided with small disc gauges at its centre and at one of its corners. About 8 ft. from one side of the large gauge was another small, fixed one having an area of about 1·5 sq. ft., and also a second disc of the same size but differing from the others in that it was free to turn. This second disc was kept pointed to the wind by means of a vane. All were read at about 9 a.m. each day for 6 years.

In addition to these tests Sir Benjamin Baker carried out tests with a wind blast on small models of trusses and lattice girders, and satisfied himself that an allowance of 1·8 times the exposed area of the front girders was ample to cover the total wind load on the front and back ironwork.

Four out of the 12 gales were at right angles to the plates used and the following results were obtained:

Small fixed gauge	.. 25, 27, 41 and 38	lb. per sq. ft.
Small revolving gauge	30, 25, 35 and 36	,, ,,
Large fixed gauge	.. 17, 19, 27 and 15	,, ,,

The remaining 8 gales were at about 45° to the gauges, so that the pressure recorded by the instruments was only about 90 per cent of the actual pressure normal to the plate. The actual readings were:—

Date	Small revolving gauge	Small fixed gauge	Large fixed gauge
	lb./sq. ft.	lb./sq. ft.	lb./sq. ft.
27/10/1884	29	23	18
28/10/1884	26	29	19
31/3/1886	26	31	19
4/2/1887	26	41	15
5/1/1888	27	16	7
2/11/1889	27	34	12
19/1/1890	27	28	16
25/1/1890	27	24	18

As this bridge was designed for 56 lb. per sq. ft. these results show an unnecessarily large factor of safety.

Bidston Observatory, near Liverpool.—Pressures were measured simultaneously on a cup anemometer and on a plate 2 ft. square. The instruments used were a Robinson cup anemometer for measuring velocity and an Osler spring-pressure anemometer for recording pressure. The results are given on page 409.

With reference to these figures for Bidston Observatory, it has been pointed out that, as no damage was done, the figures are obviously useless and inaccurate. W. H. Dines in the section on "Anemometers" in the *Encyclopædia Britannica* says that several of these have been erected on the West Coast of England, where in winter fierce gales occur. A pressure of 30 lb. per sq. ft. has never been recorded by them, and pressures exceeding 20 lb. per sq. ft. are extremely rare.

* *Reale Comitato Telassographico Italiano*, 1912, Memoria 8, p. 37.
† *Engineering News Record*, 1917, vol. 79, p. 733.
‡ *Engineering*, 1890, vol. 49, p. 219.

That these figures are inaccurate is shown by the tests made on the Forth Bridge, where an average reduction of 40 per cent is necessary on the value of the pressure recorded on the small plate in order to obtain the true value registered on the large plate.

Eiffel Tower observations (1889).*—Records were taken at two points simultaneously, viz. at elevations of 69 ft. and 1 064 ft. Of these records, taken on 101 days, the average velocity was 4·9 m.p.h. at the bottom point of observation and 15·7 m.p.h. at the top. The velocity at the top was greater than 17 m.p.h. for 39 per cent of the time and greater than 22 m.p.h.

Date	Pressure on plate	Velocity
	lb./sq. in.	m.p.h.
23/1/1884	70·2	78
20/5/1887	65·2	78
26/1/1888	49·2	74
20/11/1888	49·0	71
3/5/1888	44·4	66
30/3/1886	41·9	62
26/10/1884	40·6	64
9/12/1886	40·4	69
3/2/1887	40·1	66
1/11/1887	40·0	57

From this $p = K \times 0{\cdot}0027v^2$, and $K = 3{\cdot}8$ (average); or $p = 0{\cdot}01v^2$ (Tay Bridge Commission Report).

for 21 per cent of the time. The following intensity ratios were found experimentally:—

$$\frac{V_{\text{top}}}{V_{\text{bot.}}}\begin{cases}= 5\\ = 4\\ = 3\\ = 2\end{cases} \quad \text{when } V_{\text{bot.}}\begin{cases}= 3 \text{ m.p.h.}\\ = 4 \quad ,,\\ = 5 \quad ,,\\ = 7 \quad ,,\end{cases}$$

The S.P. Wing experiments at Ballybunion.†—In 1916, S. P. Wing made a contribution to the knowledge of this important subject, the value of which can best be judged by the remarks of R. Fleming in an article on "Wind Pressures at High Elevations and their Applications to Radio Towers." ‡ The investigation was carried out on 492, 300 and 15 ft. levels, and being on radio masts the results obtained are of considerable practical value. Mr. Wing came to the conclusion, although fully recognizing the incomplete and unsatisfactory nature of the results obtained, that the increase of pressure with elevation follows a law approximating to

$$P = (0{\cdot}00126h + 1{\cdot}16)P_g$$

where P = pressure in lb. per sq. ft. at a height h above ground level; and

P_g = pressure in lb. per sq. ft. at ground level.

For example, with an assumed pressure, P_g, of 27 lb. per sq. ft., corresponding to a wind velocity of 80 m.p.h., the pressure P at an elevation of 820 ft. would be 59 lb. per sq. ft., with a corresponding wind velocity of 118 m.p.h.

* *Scientific American Supplement*, 1890, vol. 30, page 12121.
† *Electrician*, 1921, vol. 87, p. 6.
‡ *Engineering News Record*, 1922, vol. 88, p. 438.

Some Examples of Wind-pressure Assumptions in Connection with Radio Towers and Chimneys.

In 1911, specifications issued by the United States Government for a square tower 200 ft. in height called for a wind pressure of 50 lb. per sq. ft. In a specification issued in 1914 for 300-ft. triangular towers to be erected at Key West, Florida, the specified pressure was 30 lb. per sq. ft. Towers, 600 ft. in height, built at Guam have the wind-pressure assumption of 30 lb. per sq. ft. cast in the nameplates.*

In the case of the tallest self-supporting steel stack in the world, i.e. at the plant of the United Verde Copper Company, of Clarkdale, Arizona, with an elevation of 400 ft. and a diameter of 30 ft., the wind pressure assumed was 25 lb. per sq. ft.†

The brick chimney at Great Falls, Montana, was for a time the highest in the world, being 506 ft. above its foundations with an internal diameter of 50 ft. at the top. The wind-pressure assumption was 33 lb. per sq. ft. of projected area and this factor was determined upon after due consideration of the height, the altitude and the very severe winds prevalent in the locality.‡

A similar chimney made by the same company at Tacoma, Washington, in 1917 is 573 ft. high and 25 ft. in diameter at the top. At Anaconda, Montana, is the highest chimney in the world, with a height of 585 ft. above the foundations and 60 ft. internal diameter at the top. In the design of these two chimneys a wind pressure of 33 lb. per sq. ft. of projected area was assumed.§

In the design of a reinforced concrete chimney 570 ft. high with an internal diameter of 26 ft. 3 in., built at Saganoseki, Japan, in 1916, the wind pressure assumed was 25 lb. per sq. ft. of projected area.‖

Marks in his "Mechanical Engineer's Handbook" gives for guyed steel stacks a wind pressure of 25 lb. per sq. ft. of projected area.

The triangular towers at Arlington, Virginia,¶ of which there are two 450 ft. and one 600 ft. in height, were designed for a pressure of 30 lb. per sq. ft., as also were the 600-ft. towers at San Diego, Pearl Harbour and Cavite.

For a standard 820-ft. triangular tower proposed for Fort Monroe, U.S.A., the specification called for 30 lb. per sq. ft. on 1·5 times the area of the front face.**

In connection with these figures R. Fleming says that, according to the U.S. Government formula for towers erected near the coast, the actual wind velocities corresponding to recorded wind velocities of 110 and 100 m.p.h. are 82·9 and 76·1, which (using the formula $p = 0{\cdot}004v^2$) gives 23 lb. per sq. ft. for a

* *Engineering News Record*, 1919, vol. 83, p. 662.
† *Ibid.*, p. 500.
‡ *Engineering Record*, 1908, vol. 58, p. 600.
§ *Engineering News Record*, 1919, vol. 83, p. 501.
‖ *Ibid.*, p. 501.
¶ *Journal of the American Society of Naval Engineers*, 1913, vol. 25, p. 60; *Engineering News Record*, 1919, vol. 83, p. 662.
** *Engineering News Record*, 1919, vol. 83, p. 662.

recorded velocity of 100 m.p.h., and 27·5 lb. per sq. ft. for a recorded velocity of 110 m.p.h.

Mr. Fleming also adds that he believes that with the assumption of 30 lb. per sq. ft. on 1·5 times the exposed area of one face, working stresses of 18 000 lb. per sq. in. in tension and $(18\,000 - 70l/k)$ in compression are permissible for all loadings, where l = length of column in compression, and k = least radius of gyration. His preference is for 30 lb. per sq. ft. on 1·75 times the area of one face, 20 000 lb. per sq. in. for tension and $(20\,000 - 90l/k)$ for compression.

The J. G. White Engineering Corporation built 10 stations in which the 79 masts consisted of a steel tubular pattern built up of half or quarter cylinders, and ranged in height from 300 ft. to 500 ft. In this design a wind pressure of 30 lb. per sq. ft. of projected area was assumed.

R. Weagant in an article on "Design and Construction of Guy-supported Towers" * gave a worked

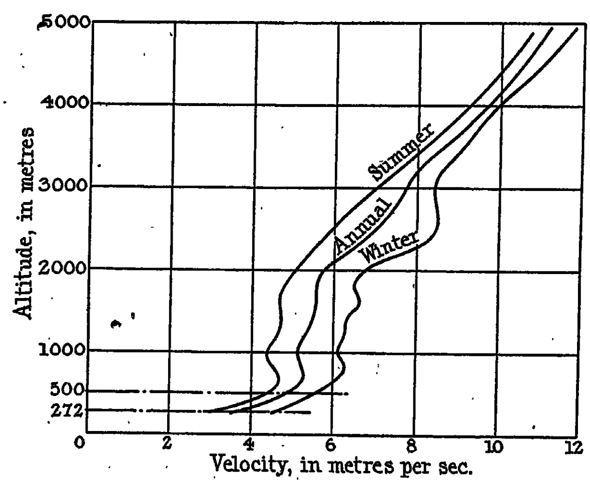


FIG. 1.—Increase of wind velocity with elevation (after Fabris).

example of a 625-ft. tubular mast. His assumed wind loads were as follows :—

Up to 100 ft. elevation, 15 lb. per sq. ft. of projected area.

From 100 to 200 ft. elevation, 16 lb. per sq. ft. of projected area.

From 200 to 300 ft. elevation, 21 lb. per sq. ft. of projected area.

From 300 ft. to top, 25 lb. per sq. ft. of projected area.

Radio Central Station of the Radio Corporation.†—In the recently constructed station at Port Jefferson, Long Island, U.S.A., the towers, of which there will ultimately be 72, are 400 ft. in height. The wind load assumed in the design was 30 lb. per sq. ft. on twice the projected area of one face for the top 300 ft., and a similar figure on 1·5 times the face for the lower 100 ft.

Radio Station at Croix D'Hins, Bordeaux, France.—

The eight towers, each 820 ft. in height, were designed by the Bureau of Yards and Docks, U.S. Navy, and constructed by the Pittsburgh Des Moines Steel Co. The wind pressure assumed was 30 lb. per sq. ft. on 1·5 times the area of one face.

Marconi Company 820-ft. tower specification.—In a specification issued in 1919 by the Marconi Company for 820-ft. steel towers, the wind pressure specified was 30 lb. per sq. ft. on the whole of one face in the direction of the wind, and a similar pressure on the back.

Imperial Wireless Commission specification.—In a specification recently issued by the General Post Office, covering 820-ft. masts for the Imperial wireless chain, a wind pressure of 60 lb. per sq. ft. over the entire

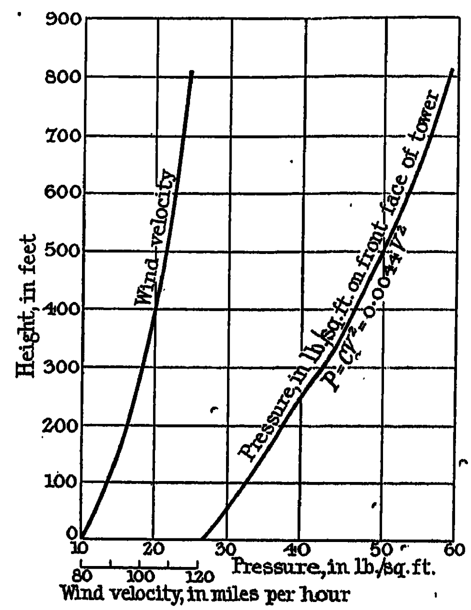


Fig. 2.—Increase of velocity and pressure with elevation (after Wing).

height of the mast is specified on 1·6 times the front-face area for triangular masts, and 1·8 times the front-face area for square-section masts.

Head frames.—M. S. Ketchum in his "Structural Engineer's Handbook" specifies for wind loads on head frames a pressure of 50 lb. per sq. ft. acting on the projection of the members of the head frame. R. Fleming says: "The load of 50 lb. seems excessive even for head frames in locations subject to high winds."

CONCLUSION.

Many more examples of the variety of specifications employed in the past for the pressures due to wind could be quoted, but sufficient have been given to prove considerable difference of opinion. By tabulating the data and reducing to a common form of expression, e.g. the total pressure on the structure in lb. per sq. ft. of the front face, the divergence of opinion can readily be seen to be from 15 to 112 lb. per sq. ft.

In building design, the assumption that the wind

* *Proceedings of the Institute of Radio Engineers*, 1915, vol. 3, p. 135.

† *Engineering News Record*, 1922, vol. 88, p. 438.

pressure at the top is the same as at ground level may not be productive of any harmful results. In radio mast and tower design the load due to the wind is, however, the chief load. Masts when unloaded are held vertical and designed to lie in a straight line, or as an arc of a circle when fully loaded. A wrongful assumption as to wind-pressure distribution from the top of the structure to the bottom can readily upset the designer's calculations as to the position which the mast will take up in a gale.

In order to appreciate the economic waste which is present in employing 60 lb. per sq. ft., for example, over the entire height of an 820-ft. mast, as opposed to a graded wind pressure of from 27 to 59 lb. per sq. ft. as shown on Fig. 2, the comparative quantities of structural steel, stay wire and concrete have been calculated. If, as is very possible, the assumption of 27 to 59 lb. per sq. ft. should be excessive and one-half of these values be sufficient, then the further possible percentage saving is also shown.

	60 lb.	27–59 lb.	13·5–29·5 lb.
Structural steel	128	100	75
Stay wire	140	100	50
Concrete	155	100	50

We have no definite knowledge as to how wind pressures, especially high wind pressures, vary with elevation, but it seems clear that they are not the same at the ground as at, say, an elevation of 1 000 ft., and the evidence points to the top pressure being more than double the pressure at the ground, so that it is not a negligible factor. The designer then seems to be more nearly approximating to actual condition if he adopts such a curve as Fig. 2 than if he assumes the same pressure both at the top and at the bottom of the structure. In our own design work we use this curve for lack of knowledge of one which more nearly approximates to actual conditions. Perhaps the discussion on this paper will bring forth hitherto unpublished data taken at radio stations or elsewhere, which will cause us to modify our views.

If it prove that no more data exist on this important subject than have been brought out in this paper, it seems to indicate that we should attempt to gain this knowledge without delay. With the large number of high radio masts and towers which have been built in recent years, there are many opportunities for fixing recording anemometers or pressure indicators at ground level, at the top and in as many intermediate positions as funds will permit. If this paper should serve to inspire any of the owners of high radio masts or towers to equip them with the necessary recording instruments with a view to filling a void in our knowledge, it will not have been in vain. The Imperial Wireless Commission, the Radio Research Board, the National Physical Laboratory and the British Meteorological Office acting in collaboration with the owners of high masts could soon produce a much more accurate solution of this important problem. If the Wireless Section of this Institution would take an active interest in the solution of this problem, more satisfactory data would soon become available.

In conclusion, one cannot do better than quote the *Encyclopædia Britannica* in connection with power-transmission towers, to the effect that "the actual possibility of wind pressure is very generally over-estimated and has resulted in much needlessly costly construction."

APPENDIX.

Summary of some Wind-pressure Assumptions.

	Wind pressure	Value of K	Pressure on front face	Remarks
	lb./sq. ft.		lb./sq. ft.	
Tay Bridge girders	56	+ 28	84	Open spaces < $\frac{2}{3}$ total outline
Tay Bridge girders	56	+ 42	98	Open spaces $\frac{2}{3}$ to $\frac{3}{4}$ total outline
Tay Bridge girders	56	+ 56	112	Open spaces > $\frac{3}{4}$ total outline
Forth Bridge design	56	1·8	101	Sir B. Baker considers excessive
U.S. Government	50	1	50	200 ft. square tower, 1911
U.S. Government	30	1	30	300 ft. triangular towers, Key West
U.S. Government	30	1	30	600 triangular towers, Guam
United Verde Copper Co.	25	1	25	400 ft. steel stack ; 30 ft. top
Great Falls, Montana	33	1	33	506 ft. steel stack ; 50 ft. top
Tacoma, Washington	33	1	33	573 ft. steel stack ; 25 ft. top
Anaconda, Montana	33	1	33	585 ft. steel stack ; 60 ft. top
Saganoseki, Japan	25	1	25	570 ft. concrete tower
Marks's "Handbook"	25	1	25	Recommended for guyed steel stacks
Arlington	30	1	30	450 ft. and 600 ft. towers
San Diego	30	1	30	600 ft. towers

[*Continued on page* 412.

APPENDIX—*continued.*

Summary of some Wind-pressure Assumptions.

	Wind pressure	Value of K	Pressure on front face	Remarks
	lb./sq. ft.		lb./sq. ft.	
Pearl Harbour	30	1	30	600 ft. towers
Cavite Harbour	30	1	30	600 ft. towers
Fort Monroe	30	1·5	45	820 ft. tower
R. Fleming	30	1·5	45	General recommendation
J. G. White & Co.	30	1	30	79 tubular masts
R. Weagant	15	1	15	Round masts, up to 100 ft.
R. Weagant	25	1	25	Round masts, over 300 ft.
Port Jefferson	30	1·5	45	400 ft. towers, up to 100 ft.
Port Jefferson	30	2	60	400 ft. towers, over 300 ft.
Bordeaux	30	1·5	45	820 ft. towers
Marconi Co.	30	2	60	820 ft. specification
Imperial Wireless Commission	60	1·6	96	820 ft. mast
Head frames	50	1	50	Fleming regards as excessive

Discussion before the Wireless Section, 10 January, 1923.

Dr. W. H. Eccles: The information collected in the paper is, of course, largely meteorological, but it is also interesting to constructional engineers because it gives definite data and facts about existing structures of great altitude. The author emphasizes two main issues. The first is that the grading of the wind pressure with height ought to be adopted in designing masts and towers for wireless purposes, and the second is that many of these high structures are unnecessarily costly because windage and safety factors of too large value have been assumed by cautious designers. With regard to the first point, the grading of wind pressure, the author discusses the subject from the point of view of measurements in the open air under fairly ordinary conditions. It is well known that in all ordinary air movements the velocity at ground level is much smaller than that at a height of 1 500 ft., where the velocity attains a value approximating to the theoretical value computed from the isobars on the synoptic charts. This distribution of velocity seems to hold good also in heavy winds and even in gales; but it is not for those conditions, which we may call peace conditions, that the designer of a mast has to work. No mast reasonably strong has fallen down under ordinary air movements. One has to design for a time of crisis when the motion of the air is so turbulent that probably all the data and theory which we have had put before us break down. For example, if two extreme cases of air movements, such as those in England and those in Hong-Kong, be considered, it will be found that there are at least two different types of atmospheric crisis. The type we have in England usually appears as a "line squall." These are not very frequent—possibly they come about once in 10 years on the average—but it is for such conditions that the designer of masts has to prepare. He dismisses all considerations that are based on the measurement of air velocities during the preceding 10 years of peace; he has to think of the 30 seconds of crisis. During a line squall the motions of the air are quite different from those in normal conditions. In these islands the line squall is produced by a cold wind usually coming from the west or the north-west almost broadside on to a mass of warm air which would otherwise be moving from the south. Because the velocity above is greater than the velocity below, the upper layers of the cold air push ahead of the lower layers and the border between the warm and cold air leans forward, as it were, as the motion takes place, and consequently large masses of cold air fall through the warmer air from a height of about 2 000 ft. The warm air underneath the crest of this wave of cold air breaks like a big bubble through it, and the consequence is a horizontal rolling progress of the front of the cold current of air. That rolling motion seems to have its centre at a height of about 1 000 to 1 500 ft., and it is therefore quite possible to experience for an instant a velocity near the ground greater than 60 m.p.h. and a velocity of, say, only 40 m.p.h. at 1 000 ft. up. On account of this rolling motion we may have for a few seconds a complete reversal of the conditions of which the author has told us. That, however, is not the worst of the matter from the point of view of the design of high towers, because when the warm air suddenly rises in the atmosphere the water vapour in it condenses and huge volumes of rain and hail are formed, which, descending through this cold wind below, gather a horizontal component of velocity as they fall. When the momentum of the rain, hail or snow is added to that of the wind, much higher pressures than those mentioned in the paper are obtained. What we really want, it seems to me, are the statistics of the total pressures on structures during the times of crises. The statistics taken during the preceding 10 years of peace are not of any direct value. They are of indirect value in the sense that every scrap of knowledge which we obtain enables us to make better calcu-

lations next time, or shows us how from that knowledge we can compute what happens in the turbulent condition of the atmosphere that I have tried to describe. The other extreme case I referred to, the typhoon, consists of a rotation of the air around a vertical instead of a horizontal axis. At a place like Hong Kong it seems to be expected that certain tracts of country are sure to get a typhoon every few years, and if the buildings are light enough they get removed at fairly regular periods. There are exceptions, of course, which stand for 50 or 100 years, but the insurance companies would not base their premiums on such cases. The other thing I should like to mention—and I think the author has not referred to it—is that we really must take account of the dynamics of the matter in the design of these structures. A big mast in a turbulent atmosphere rocks first one way and then the other, and the motion may be as much as 10 ft. at the top of an 800-ft. mast. This motion must tend to take place, as in the case of every fairly rigid body, about a dynamic centre fairly near the centre of gravity. The problem becomes different according to whether the mast is fixed into a massive block or has a pivoted foot. I do not know that one type is more dangerous than the other in practice, but we have less experience with the one with the swivel base. The dynamics of both prove to be very difficult, chiefly on account of the effects of the guys. If it be assumed that the mast tends to rock about the centre of gravity, it will be found that very big thrusts are imposed sideways on the base. To prepare for this the design should be such that the centre of gravity of the mast will be fairly low, lower in the case of a pivoted mast than with one footed in concrete. When all these factors are taken into account, one feels it is best to use a rather large windage value and so keep the centre of gravity low. And there are other reasons for this. The author quotes from the *Encyclopædia Britannica* that many structures are needlessly costly, but whether that is so depends upon the circumstances. If by making a structure safe 20 per cent is added to the weight, seeing that labour is such a large factor of the cost of a mast, it may be that 10 per cent is added to the cost. This 10 per cent, if it enables the mast to survive three squalls instead of falling down at the first, will be a wise insurance. For it is necessary to consider how much business would be lost while erecting a new mast after one had fallen, and also, in the case of strategic stations, whether great dangers might arise if masts were blown down. I therefore do not agree with the writer of the article in the *Encyclopædia Britannica*, but am in favour of a very good margin of insurance when not only possible commercial losses but also strategic aspects have to be considered.

Major A. S. Angwin: There is no doubt that the paper is very valuable as indicating the great discrepancy between the experimental data of wind pressures at high elevations and the assumptions made in the design of towers. I think the conclusion can be drawn that the data in the paper from different sources indicate so many discrepancies that it is very difficult indeed to form any law which would safely meet the case of the variation of pressure or velocities throughout a structure such as an 800-ft. or 1 000-ft. mast. There are some other data not quoted in the paper which rather bear on that assumption. Reference is made to the classical experiments on the Forth Bridge by Sir Benjamin Baker, but during a period of five years, 1901 to 1906, covering a much longer time, further records were made on the Forth Bridge during gales, and over that period, at a height of 378 ft. above sea level, pressures as high as 65 lb. per sq. ft. were recorded. If a figure of that order were applied to the formula suggested by the author, it would result in very much higher pressures than the assumptions which are made; they work out at something like 85 lb. per sq. ft. at the top of an 800-ft. mast, down to 40 lb. per sq. ft. at the bottom of the mast. The figure of 85 lb. is an incredibly high value and indicates that it is not safe to assume a formula of that nature. Further data published by the Meteorological Office in 1918 give values of wind velocities and also gust velocities at varying heights up to about 100 m. The analysis of the form of the curve of those results appears to indicate that at steady wind velocities there is a very marked increase of velocity with height up to about 100 ft. At greater heights the slope of the curve decreases very much. Neither of those results appears to agree at all closely with the suggested linear law attributed to Wing. From the evidence available I think that the conclusion to be drawn is that whilst for steady winds of moderate strength an assumption of the nature suggested may be made, such an assumption does not appear to be applicable for gales or for gusts. In connection with the design of structures, the designer is concerned with the concentrated gusts. In the recorded figures for the Eiffel Tower on page 409 it will be noticed that the ground velocities are very small, i.e. from 3 to 7 m.p.h. At 3 m.p.h. with a velocity ratio of 5 the wind at the top of the mast will be 15 m.p.h., whereas at 7 m.p.h. the velocity ratio is only 2 and the actual velocity of the wind at the top of the tower will be 14 m.p.h., i.e. less than at the lower figure of 3 m.p.h. at the bottom. It would seem to be a more reasonable assumption, if it is conclusive that the pressure is not constant throughout the whole of the length of the mast, to assume a steady load corresponding to a pressure of about 30 lb. per sq. ft. for the whole of the structure, and superimpose thereon a live load of the order of 20 to 30 lb. per sq. ft., which might be applied in lengths not exceeding 100 ft. That would appear to correspond more closely to the conditions which might occur during a violent storm. The question of the allowances to be made for wind pressure on the back of the mast is briefly referred to in the paper. There must now be a great deal of data available from experimental determinations. The only possible way to find the exact value of K is by experimental determination in wind tests, and, as suggested by the author, any data of that nature would be of very great help in treating the question of the design of masts.

Mr. Oluf Trost: The shape of the curve shown in Fig. 2 is largely dependent on local conditions and it

may for the same mast vary for different directions of the wind. More recent Eiffel Tower observations give a different curve altogether. On the other hand, a wind velocity of 100 m.p.h. or more has not yet been recorded since the tower was built, 33 years ago, which perhaps accounts for the fact that masts in France are made lighter than one would care to make them in other parts of the world. I do not agree with the figures which the author puts forward to show what economy could be obtained in material with a reduction in wind pressure. In mast construction there are so many factors to take into account that the economic waste in assuming a fairly high wind pressure is not so very large. In a well-designed construction consideration has to be given to minimum sizes of material, upkeep, erection and many other things. I quite agree that it would be of great importance to obtain as many statistics as possible from all parts of the world, especially as to the probability and regularity of "super-wind" velocities occurring in different places. It would also be of great interest to learn whether there is any relation between the average wind load and the maximum wind load, including the frequency with which the latter occurs. It might be possible to find some relation between these factors so that it would be more easy to know with some certainty the maximum loads to which a mast will be exposed, when built in a certain place. Finally, I should like to point out that the figures mentioned as being the wind pressures specified by the Marconi Company are now out of date and that the designs are based upon wind pressures of from 30 to 50 lb. per sq. ft. of surface exposed to the wind, the figure varying with the height of the masts.

Mr. Andrew Gray: I agree with the author that, in general, wind pressure is more than amply provided for in present practice by reason of the ample factors of safety. The problem is, however, complicated by the presence of wind eddies. In some cases these eddies add to the loads by producing oscillations, while in other cases they may reduce the load; for example, a long span of wire may be locally heavily loaded but as a whole partly supported by the eddies. I remember in particular the effects of the hurricane on the island of St. Vincent, West Indies, in September 1898. Almost every house was unroofed, including the library—a good stone building in Kingston—although the walls remained standing, and the branches of the trees were torn off the trunks, but few of the trees were blown down. In the case of an avenue of palm trees leading to Government House the heads of the palms were torn off but the palm trunks, some 30 or 40 ft. in height, remained standing. There was not the slightest doubt in my mind that in this case the major damage was done by the eddies. In the case of another hurricane, that in Fiji in 1912, it was reported to me at the time that the roof of the wireless station engine-house was torn off, but the mast—a 150-ft. sectional steel stayed mast with a wooden top—remained standing, again indicating the presence of eddies. The effect of these eddies is to produce great pressure at particular instants over small areas, but the maximum pressures do not occur simultaneously over the whole of a large area or an extended structure such as a mast or aerial. On the other hand, these eddies where they do occur act to a considerable extent like a blow and have to be considered in that way, and one has to be satisfied that in any mast or tower design a suddenly applied local blow will not cause stresses in excess of those allowed by the dead-load calculation and factor of safety.

Professor C. L. Fortescue: The load carried by a mast arises from the wind pressure on both the mast and the aerial. If the proportion of the load due to the latter is large it follows that the wind pressure at the top of the mast is the most important factor. Perhaps the author will say in his reply what relative values he has actually found for these two contributions to the total load. If a large factor of safety is allowed for the load arising from the aerial it may explain how it is that satisfactory service has been given by those masts in which low wind pressures have been assumed.

Professor G. W. O. Howe: This is a very highly specialized subject, appealing only to a small number of wireless engineers. When reading the paper I had some doubt as to what was intended when it is stated that the specification called for certain wind pressures —whether the masts were supposed to stand satisfactorily at those specified wind pressures with a reasonable factor of safety, or whether they are the limiting wind pressures at which the tower is supposed to collapse. I am surprised that so little is said in the paper as to the factor of safety to be allowed in the various cases, as it seems to me to be useless to specify any definite wind assumption without at the same time specifying the factor of safety to be allowed; I should like some further information on this point. The author mentions the Bidston experiments and states on page 409: "That these figures are inaccurate is shown by the tests made on the Forth Bridge, where an average reduction of 40 per cent is necessary on the value of the pressure recorded on the small plate in order to obtain the true value registered on the large plate." I do not know why one is justified in assuming that the large plate should give the true value. Two plates were put up and it is assumed that because they differ the large plate gives the true value. I do not know whether there is any proof that a still larger plate would not have given an entirely different value.

Mr. A. C. Brown: Has any account been taken of the effect of snow on the wires? I know of cases where the temperature at the commencement has been rather high, with wet snow. Afterwards, when the temperature fell and the snow was frozen, the wires became of very large diameter. I think that that point has to be considered, as it is quite possible that the final diameter of the aerials when covered with ice will be 4 or 5 inches.

Mr. S. P. Wing (*communicated*): The paper brings under discussion a subject the importance of which I think is not ordinarily realized by electrical engineers. An electrical engineer is ordinarily responsible for the complete installation of large wireless installations. He gives great care to the most efficient type

of electrical equipment to be used and works carefully to gain an extra efficiency of perhaps 10 per cent in his electrical apparatus. Yet when it comes to the question of the aerial structure he is often content to specify in a general way the wind and antenna loads and leave the mechanical design of the masts and antenna to the civil engineer, without realizing that these two items largely control the cost of this portion of a wireless station. Since the aerial structure with the antenna represent from 40 to 60 per cent of the cost of a complete station, it is seen that unnecessarily severe loadings in this regard may easily run away with the 10 per cent saving he has effected by efficient electrical design. For example, the electrical engineer may have used a large amount of wire in his antenna (thus causing heavy mechanical antenna loads) to gain an extra 5 per cent antenna efficiency, when a greater saving could perhaps be made by tightening the antenna and thus gaining effective height. Alternatively, a smaller antenna load could be used and a higher mast built. The author gives comparative figures showing the average charge of certain large items which make up the cost of a wireless mast under three conditions of wind loading. Approximately these represent two-thirds of the entire cost, the other items not varying with the wind loading. On this basis the percentage cost of a mast under the three conditions which he has shown is 127, 100 and 72. Wireless masts have been built under the first two of these classes of loading. Assuming 8 masts 800 ft. high, this might represent an expenditure of £125 000, 27 per cent of which is £34 000. With such sums in question and with larger stations yearly being erected it would seem that the author's plea for more data on wind loading is well justified and that interested parties could well afford to spend the few hundred pounds necessary to obtain these data. I believe that the confusion existing in regard to wind specifications, examples of which are so numerous in the paper, is due to the fact that the wind loads are those assumed by structural engineers, these loads in ordinary design being of little economic importance. Equally in wireless masts of small heights such loading is of small matter. Yearly, however, the height of masts has increased and with this the importance of the wind loading, until now it is the major load. No bridge designer would think of basing his design on a haphazard covering load, and equally in the future no electrical engineer should specify the wind loading for a wireless mast without the most careful consideration, for otherwise the civil engineer is bound in the most vital factor affecting the economics of his design. I realize the necessity for a mast in which there can be no question of failure, but if larger factors of safety are required than those used in ordinary building practice such factors should be obtained by increasing the safety factor rather than by specifying an unnecessarily large wind load. Take, for example a uniform specification of a loading of 60 lb. per sq. ft. We have no knowledge of such a wind loading occurring near the ground (say under 100 ft. elevation). We surmise that such a load may occur at 800 ft., though such velocities as this loading implies have seldom, if ever, been measured. Obviously, if we wish to ensure the safety of our structure, it is wiser not to assume a uniform heavy wind load causing smaller factors of safety at the top of mast than at the bottom, but to use a graded load as the author suggests or (perhaps better) adopt the suggestion of Major Angwin and superimpose a graded live load on a probable wind load. To adopt such a specification intelligently, however, we must have the further data for which the author appeals. Throughout the paper he lays emphasis on wind-pressure assumptions. This is natural, as he is quoting from past experience and records. I believe that such past procedure is wrong and that it is something which wireless engineers can correct. The majority of wind records are based on velocities which are measured direct. Where pressure is measured this is of little use to the wireless engineer. Such a statement would have been difficult of explanation a few years ago, but with the advent of the aeroplane it is increasingly realized that for every different surface the factor K (in the common formula for changing velocity to pressure, i.e. $P = KV^2$) varies. For this reason the pressure as measured by a Pitot tube bears little relation to the pressure on, say, a long angle. From this it follows that in comparing two mast designs of different type but to a common specification of, say, 30 lb. on $1\frac{1}{2}$ times the front-face area, no true decision can be made as to their relative strength for, depending upon the type of mast and size of members, the factor K varies. Under a given wind velocity the effective loads on the mast, as computed by the specification with a constant factor K, may not represent the true state of affairs. The only satisfactory method is for the specification to be in terms of velocity and then for designers to have small-scale models of the proposed structure tested in wind tunnels to determine the coefficient K. This can be done at small expense, and an accurate knowledge of the loads which given wind velocities will impose can thus be obtained. I have tried to show above how one of the uncertainties of wind loading can be eliminated. If the paper and the discussion induce the authorities to make the experiments which the author suggests, I believe that electrical engineers will be in a position to issue wireless mast specifications which will ensure that the aerial system is designed as efficiently as the electrical apparatus.

Mr. C. F. Elwell (*in reply*): Dr. Eccles gives a very interesting explanation of meteorological conditions in England, and also in Hong-Kong, and points out the necessity for designs to meet the two different conditions of wind loading. But from my experience with high masts in heavy winds I cannot agree that the motion may be as much as 10 ft. at the top of an 800-ft. mast. In the design of an 800-ft. mast I use a deflection of 1 per cent at the top; this represents an assumed maximum movement of 8 ft., and correspondingly smaller movements at each of the lower stay points. Now, due to gusts and eddies the tower does oscillate, not, however from 8 ft. on one side of the vertical to 8 ft. on the other side, but, for example, 1 ft. back and forth from the line of the position which it has taken up due to the steady wind pressure, or a total

movement of only 2 ft. The average velocity, and with it the pressure which holds the mast away from the vertical, tends to increase and decrease rather slowly due to the effect of gusts, perhaps varying not over 10 per cent from the mean value. The inertia of the mast and its stays has also to be considered, in view of the fact that the gusts are of relatively short duration. That the thrusts on the pivoted bases may be very big is also doubtful. Pivoted masts up to 850 ft. have been constructed. The figure for the horizontal component acting at the bottom is only a few per cent of the total vertical load, and this horizontal thrust is actually taken up by the horizontal force due to friction from the large vertical loads. It is usual, however, to provide horizontal stops as an additional precaution.

Major Angwin adds some interesting data to those which I have tabulated. I have not been able to find the data to which he refers and I should be pleased to know where they are to be found. Much of the pressure data published previous to 1910 is faulty, due to the inaccuracy of the formulæ changing measured velocities into the desired factor pressures. It is possible that the pressure of 65 lb. mentioned is due to this, and is not a corrected figure corresponding to the modern formula. It must be remembered that, from the point of observation, the Forth Bridge is 378 ft. above ground or sea level. I know of practically no records in England of wind pressures as high as 30 lb. close to the ground, and only three or four of 30 lb. at 200 ft. elevation (Pendennis Castle). Major Angwin's suggestion of a steady loading of 30 lb. with a superimposed live load of the order of 20–30 lb. per sq. ft. in lengths not exceeding 100 ft. can be plotted in the form of a curve, if applied to a mast of, say, 800 ft. in height. This curve would have a form somewhat similar to that proposed. But due to the rarity of 30-lb. winds at ground level it would seem to be unnecessary to add any live load here. In effect the curve of Fig. 2 can be considered as adding 15 lb. at 400 ft., and 30 lb. at 800 ft. elevation to a ground pressure of about 30 lb. If more data could be recorded and the shape of the curve of increase of wind pressure with the height more accurately obtained, I think that engineering economics would be better served than by the many and varying guesses of the past. One thing to be said in favour of Mr. Wing's curve is that it is the only attempt of which I know to measure actually the velocities at heights low enough to interest radio engineers, and it is fairly well substantiated by the measurements of Dr. Fabris. Of course the topography of the neighbourhood has some bearing on the increase of pressure with height, especially from ground level to 100 ft. The question of allowances to be made for wind pressure on the back of the mast was only briefly referred to in the paper, as it is proposed to make a further communication on this subject at a later date.

Mr. Trost points out that consideration has to be given to minimum sizes of material, etc., and this is well recognized, otherwise the figure for 13·5/29·5 lb. wind assumption would have been 50 for steel, instead of 75. The figures given are round figures, but were obtained by working out a complete design which had already been made for a 27/59 lb. wind. However, if any one of the three assumptions be adopted, different section lengths, etc., would be employed in order to obtain the maximum economy. With a 60-lb. wind, for example, assumed on the bottom section of a mast, the sections would be made shorter than with a 30-lb. wind, because of the large increase in stresses due to beam action. It is a recognized fact that the fewer the stays employed the heavier the steel in the mast. A 9-stay design with a 60-lb. wind all over becomes as heavy as a 5-stay design with the 27/59 lb. assumption.

Mr. Andrew Gray gives interesting particulars concerning hurricane figures. I am sceptical, however, as to the effect of eddies being like a blow, or, if so, it is my belief that they are counteracted by the inertia of the mast and its stays.

In reply to Professor Fortescue, the higher the mast the less important becomes the load due to the wind on the aerial. In a given design for a very heavy aerial, the load per column at the bottom of the mast was 6 per cent for the aerial and 94 per cent for the wind load and dead weight of the mast.

The question of factors of safety, mentioned by Professor Howe, was not brought into the paper as the engineer entrusted with the design would use the factors of safety usually employed for the class of material in question. Structural steel is usually worked on the basis of 18 000 − 70 l/k, where l = length of unsupported section, and k = least radius of gyration of the member. This represents roughly a factor of safety of 2. For the stays, factors of safety of from 3 to 4 are generally specified. The plates employed in the Forth Bridge experiments were intended to have a fixed relation to the sizes of girders used on the bridge. The most accurate method of obtaining the effect of the small and large areas in a structure under the action of wind pressure is to construct a model and test it in a wind tunnel.

Mr. Brown points out the possibility of wires becoming very large due to deposits of ice. This is a problem which has to be faced on the east coast of the United States, where in some stations electrical methods are employed for melting the ice. From a structural point of view there is not much danger in omitting the area offered by these large diameters, because it has been amply borne out in practice that high winds and coated wires do not occur simultaneously. The increasing wind pressure tends to break off the ice, and so diminishes the danger.

Mr. Wing refers to the economics of the subject, and the question is summed up in the possibility that the expenditure of a few hundred pounds might save many thousands of pounds in future expenditure. Present wireless plans call for some 50 masts of the order of 820 ft. in height, and these may be erected in the next three years. They represent an investment of a considerable sum of money and warrant the expenditure of a substantial sum in experiments on wind pressure, wind resistances, stay wire with minimum stretch, etc.

THE MAINTENANCE OF VOLTAGE ON A D.C. DISTRIBUTION SYSTEM BY MEANS OF A FULLY AUTOMATIC SUBSTATION.

By P. J. Robinson, Associate Member.

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Summary.

The paper describes the considered methods of meeting a particular case of voltage-drop in a large direct-current lighting network and for bringing into use the maximum amount of its copper with a minimum of cost.

A fully automatic station was chosen in this instance for the reasons stated, and the author in discussing the subject has not attempted to review the relative merits of different types of automatic stations, but rather the method of dealing with a particular problem, and with this end in view has described the station which has come under his immediate control.

So far as the author is aware, the plant described is that of the first fully automatic station in this country, for any purpose, and of the first fully automatic station in existence operating a three-wire system.

The gradual growth and expansion of our cities owing to increased industrial activities and better transport facilities have brought large areas that were thinly populated suburbs into close touch with the city, and caused them to be more densely populated. This has meant that the original electric supply systems laid down, in some cases many years ago, have gradually extended until such time as the length of feeders has become troublesome owing to the voltage-drop.

In the event of the system being originally an alternating-current system and remaining so, this has been overcome by installing transformers at suitable points in the system to maintain the pressure. Where, however, the system was originally a direct-current one, the engineer was faced with a much more difficult problem, more particularly in the residential areas, as d.c. plant had to be installed, which meant buildings to house it and staff to operate it. The latter item is particularly expensive, as the stations are worked on a more or less low load factor; also the staff salaries and operating costs do not increase in direct proportion to the capacity of the station. This fact has led to larger and fewer substations at long distances apart.

The more extensive use of domestic apparatus has had the effect of raising the average load taken by consumers from ½ kW to 1 kW for lighting, up to 5 or 6 kW on the average when domestic apparatus such as radiators, cookers, vacuum cleaners, irons, etc., has been installed. This has necessitated more feeding points along the system to make full use of the copper laid down. Assuming copper at 1 000 amperes per square inch, in some cases only 30 per cent is available owing to the voltage-drop due to the length of feeders, which voltage-drop is, after all, the limiting factor in fixing the value of the distribution system.

This problem of maintaining a more constant voltage over the whole network, and at the same time keeping down operating costs and capital costs, has been exercising the minds of many electric supply engineers in this country, and Liverpool is in much the same position as other authorities. Recognizing that the matter had to be dealt with, and appreciating the alternatives, i.e. to lay new feeders, or to change over sections of the distribution to a.c. supply, building up either a new distribution system or using old d.c. mains for a.c. supply (the latter being almost prohibitive, due to the cost of changing consumers' apparatus, motors, battery-charging sets, and many other pieces of apparatus not fitted with universal motors), it was finally decided to try to deal with the matter by installing fully automatically operated stations at different points of the system, thereby reducing operating costs to a minimum, and at the same time enabling the existing mains to be utilized to the best advantage.

Fully automatic control and remote automatic control of converter plant have been in use in America for lighting and traction purposes, and also in Switzerland for traction purposes, for some time past.

Remote control has also been in use in this country on several systems with more or less success, but British engineers appear to have fought shy of fully automatic control, and it has been left to Liverpool to lead the way in this direction. The Electric Supply Department decided that all conditions existing in Liverpool could be met by this control and that, apart from periodical inspection of plant, operating labour could be eliminated.

Acting on this decision a general scheme was evolved for the control of a three-wire system with the conditions that would have to be met in Liverpool, also covering various points on which we must insist. Having chosen a site adjacent to Walton Town Hall, midway between two of our existing manually operated substations, namely, Cobbs Quarry and Rice Lane, we submitted the scheme to various manufacturers of automatic gear. The scheme and conditions were as follows:—

(1) The station to have a capacity of 500 kW, with room for extension.

(2) The station should cut in after the pressure on the low-tension feeder bars had fallen and remained low for a predetermined time. (This time-lag was to avoid the station cutting-in with temporary falls in voltage.)

(3) The station should cut out after the current on the busbars had fallen and remained low at some fixed figure for a predetermined time; the latter was to avoid the station cutting-out

with temporary falls in load. This was also to enable the existing manually-operated stations to pick up the load when the conditions were such that the voltage could be maintained at normal.

(4) The station to operate plant running across a three-wire system, 230 volts between each outer and the neutral, and to maintain a balance in pressure.

(5) The station should operate in parallel with other stations, and other plant in the same station at a later date.

(6) If the load demanded due to existing manually operated stations shutting down was greater than its capacity it should not cut in, and, if already running, the output should be limited to the capacity of the plant.

(7) In the event of a fault on either the negative or positive side of the system, the automatic switch controlling that particular circuit should operate to cut it out, without interference with any other circuit.

(8) In the event of a short-circuit on the outers of a feeder that feeder should be cut out without interference with any other circuit or the running of the plant generally.

(9) The middle wire of the system being earthed through a limiting resistance at the manually operated stations, it was decided to deal with an earth fault from those stations.

The above conditions having been agreed upon, arrangements were made for dealing with them satisfactorily, and also to meet any difficulties due to faults on the plant itself or any connections therewith. It was then decided to proceed with a station equipped as follows:—

(1) One tap-started 500-kW rotary converter (with brush-lifting gear) coupled through its transformer to the 6 000-volt, three-phase, 50-period supply on the one side, and on the other to a three-wire system with 460 volts across the outers and 230 volts to the middle wire, the latter being connected to a tapping on one leg of the transformer supplying the rotary converter.

(2*a*) One high-tension cubicle of moulded stone equipped with an electrically operated oil switch with alternating-current closing coil; this switch to control the rotary converter.

(2*b*) Two liquid fuses to control the operating transformer (15 kVA) which supplies the operating coils on most of the relays and must therefore be permanently connected to the line.

(2*c*) One three-phase potential transformer for various instruments.

(2*d*) Necessary isolating switches.

(3) Low-tension d.c. panel for rotary converter, equipped with knife switches and electrically operated contactors in the main circuit, with ammeters on each pole, a voltmeter, and field regulator.

(4) Low-tension feeder panels for control of four three-wire feeders, equipped with electrically operated contactors in the main circuit and knife switches in the operating circuit to control the main contactors in the event of a feeder requiring to be "laid off."

(5) Other panels to have mounted thereon numerous relays, devices and contactors, the description of which will be found in Appendix A, and the operation of which will now be described.

In the diagram on page 419 the connections are arranged schematically, the numbers corresponding to the description and operation of the individual apparatus.

The automatic operation is started by means of a low-voltage d.c. relay (1), which operates to close its contacts when the voltage on the d.c. busbars drops to a predetermined value due to the line voltage-drop consequent upon a certain demand for power. When the contacts of relays (1) are closed they insert, through an interlock on the main oil circuit-breaker (20), the operating coil of an a.c. voltage relay (2). This relay has a time-lag of a few seconds and its function is to prevent the station starting due to a sudden drop in the d.c. network voltage, and also to prevent the station from starting when the a.c. voltage is abnormally low. When the contacts of relay (2) are closed they establish a circuit through the master relay (3a). The contacts of relay (3a) are then closed and complete a circuit through the operating coil of relay (3) which completes the closing circuit of (3a) to hold it in.

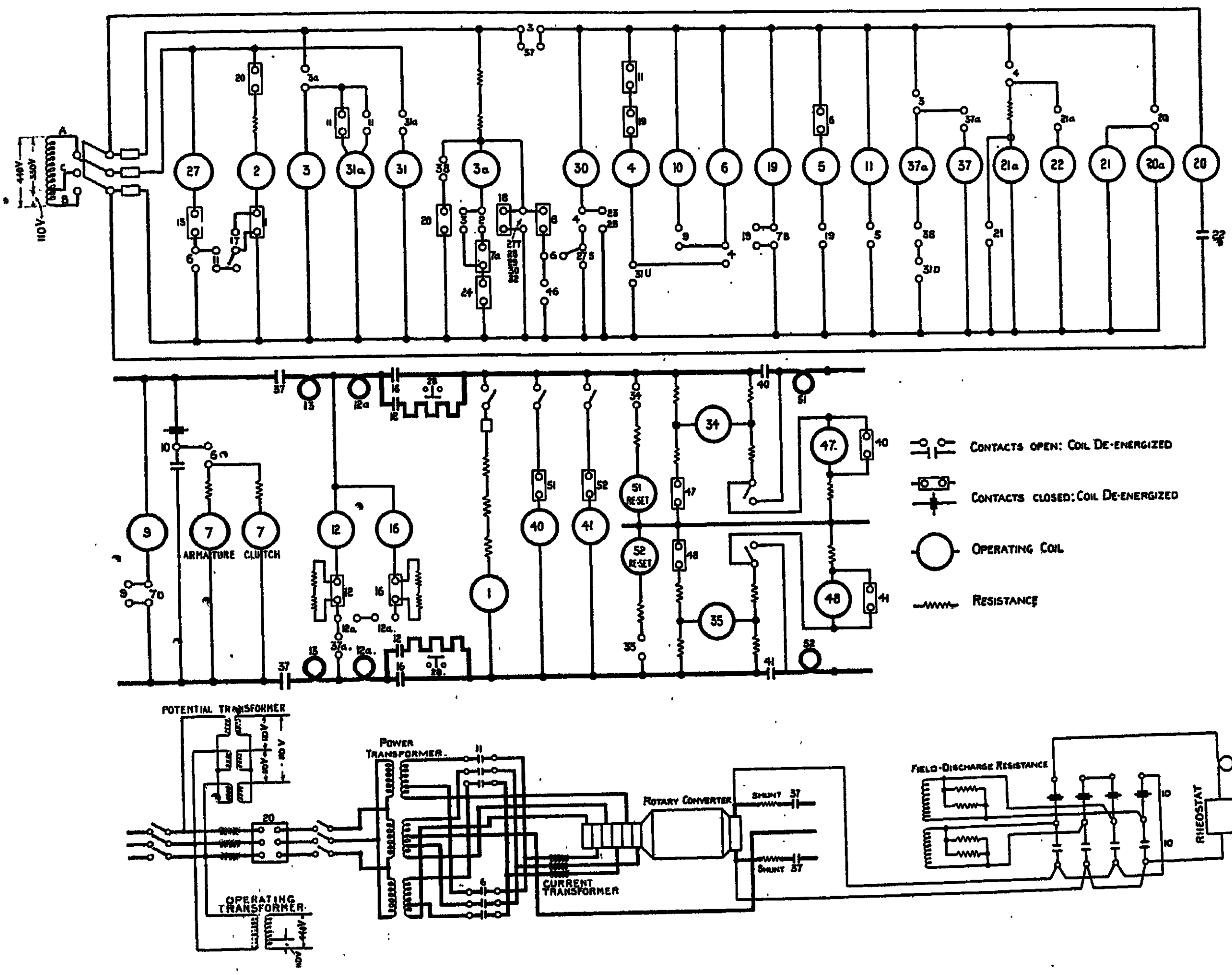
The contacts of relay (3a), when closed, also complete the circuit, through an interlock on the running contactor (11) of the operating coil of relay (31a), to cause its contacts to close and start the small motor of the brush-lifting device (31). This motor, by means of gears and a crank, raises the d.c. brushes from the commutator. When the brushes have been raised to the full extent, a throw-over switch operated by a crank disconnects the relay (31a) and thus de-energizes the motor. The brushes now remain in the raised position until the circuit of (31a) is again completed by the closing of an auxiliary contact on (11), which closes when the contactor closes. This starts up the motor which actuates the crank to lower the brushes on to the commutator. The throw-over switch is returned to its original position by the crank, and is thus ready to repeat the above cycle of operations when the converter is again required to start.

In series with the operating coil of relay (3a) will be found the contacts of an overspeed device (24) and also a contact (7a) in the polarized motor relay. This contact (7a) is closed only when the relay is in correct working order, and is placed in series with the coil of relay (3a) so as to ensure that, before the station can start, the operating element of the polarity relay is in the neutral position. Shunted across the coil of relay (3a) will be found the contacts of a number of protective devices.

Relay (18) is an induction-type polyphase voltage and reverse-phase relay. This relay, by short-circuiting the operating coil of relay (3a), will prevent the starting of the converter if the phase rotation of the supply is

reversed or if one phase of the supply is open. The remaining protective devices will be described later.

One main contact of relay (3) establishes the circuit for the main control busbar for the rest of the automatic apparatus. When the brush-lifting device is in the raised position it closes an auxiliary contact which completes the circuit, through interlocks on relay (19) and the running contactor (11) of the operating coil of a relay (4). One main contact of relay (4) completes the circuit of relay (21a) which in turn closes contactor (22). Contactor (22) completes the operating cause the rotary converter to be connected across the starting taps of the transformer. The converter will now start to rotate, and when it is in phase with the supply the d.c. voltage will build up with either correct or incorrect polarity. This is indicated by the action of a polarized motor relay (7), which consists of a small armature mounted so that it can rotate between the poles of a fixed permanent magnet. The armature is energized from a pair of pilot brushes on the commutator, and thus its direction of rotation depends upon the polarity of the converter. Connected to the shaft



circuit for closing the oil circuit-breaker (20), an auxiliary contact on which makes a circuit through the low-voltage trip (20a) and also through the operating coil of the induction time-limit relay (21). Relay (21) has a short time-lag, at the end of which its contacts close and short-circuit the operating coil of relay (21a), thus causing the latter to open, which in turn opens contactor (22). The opening of contactor (22) breaks the circuit of the operating coil of the oil circuit-breaker (20) which is now held in the closed position by a mechanical latch.

The other main contact of relay (4) completes the operating-coil circuit of starting contactor (6), to of the armature through reducing gears and a clutch are two pairs of contacts, (7b) and (7d). If the polarity of the converter is reversed the armature will rotate and close contacts (7d), thus closing the field-reversing relay (9) which sets up its own hold-in circuit. The closing of the main contacts of relay (9) causes the operation of the field-reversing contactor (10). This contactor breaks up the converter field into two sections, connects them in parallel in the reverse direction and thus causes the converter to slip one pole. When the converter has slipped one-half of the polar position the d.c. voltage falls to zero and the field-reversing relay (9) opens. This allows the field contactor (10)

to return to its original position, the converter then coming up with the correct polarity.

When the polarity is correct, the d.c. voltage will build up again and the polarized motor relay will rotate to close contacts (7b). When these contacts are closed they complete the circuit of the operating coil of the a.c. shunt relay (19) which makes its own hold-in circuit. An auxiliary contact on relay (19) opens the circuit of relay (4), thus causing all starting gear to be de-energized.

The main contact of relay (19) completes the circuit through an interlock on starting contactor (6) of the a.c. shunt relay (5), an auxiliary contact on which makes the battery circuit of the automatic voltage regulator. This relay (5) also makes the operating-coil circuit of the running contactor (11) which closes and connects the converter across the full voltage of the transformer secondary. The closing of running contactor (11) energizes, through an auxiliary contact, relay (31a), which in turn starts the brush-lifting motor (31) to cause it to lower the brushes.

A protective relay (38) is provided with its coil in series with the shunt field of the converter. This relay ensures that the field strength of the converter is adequate before any load can be taken. When the field strength has reached its normal value, a circuit is established through a contact on relay (3) through an interlock on the brush-lifting device (31), through the contacts of field relay (38) and through the operating coil of the auxiliary shunt relay (37a). Relay (37a) in turn closes the main contactor (37), which is in the d.c. converter circuit. Although the contacts of (37) are in the d.c. circuit, its operating energy is obtained from the a.c. circuit.

Another contact of relay (37a) completes the d.c. closing-coil circuit of the main d.c. operated contactors (12). This circuit, when closed, connects both poles of the converter to the busbars through limiting resistances. The d.c. accelerating relays, (12a) and (12b), measure the amount of load picked up and, if this is not excessive, allow contactor (16) to cut out the limiting resistances.

Should the converter during its operation become greatly overloaded, these accelerating relays will work in the inverse order and insert the limiting resistance to limit the load. If this load should persist, grid thermostats (28) will shut down the automatic equipment when the resistance grids reach approximately red heat. These thermostats will allow the station to start up again when the grids have cooled down.

The overload setting of the d.c. accelerating relays is purposely made very high to permit the full overload capacity of the converter to be utilized for short overloads. If the overloads should be of such magnitude as not to operate the accelerating relays, and should they persist long enough to endanger the windings of the converter, a thermal time-element relay (29) will shut down the converter and allow it to cool off. After such cooling the converter will again be put into service automatically. This thermal relay measures the R.M.S. value of the a.c. input to the machine. This is an accurate measure of the heating in the machine.

A d.c. reverse-current relay (32) is provided so that, if the a.c. supply should become inadequate while the machine is connected to the d.c. system, the converter will be disconnected from the line before the reverse flow of energy can damage it.

Induction overload relays (23) are provided which protect against short-circuits in the converter or converter leads. They also operate in case of a serious flash-over.

Thermostats are provided in each of the machine bearings, and, should any of these operate, a lock-out relay (30) is closed, thus taking the converter entirely out of service by short-circuiting the operating coil of relay (3a). This lock-out relay (30), whenever operated, must be reset by hand. An auxiliary contact is provided in the relay so that a signal circuit may be energized if desired. This signal circuit may operate semaphore or lights in front of the station, or send signals over a telephone or telegraph circuit to give warning of the trouble.

Relay (46) is an induction-type relay but of special construction so as to constitute an unbalanced phase-current relay. The relay coils are connected to the three current transformers in the low-tension circuits. During the starting operation the contacts of this relay are put in series with the operating coil of the lock-out relay (30) by an interlock on the starting contactor (6), and should any fault occur during the starting period the lock-out relay (30) is at once energized, thus closing down the entire automatic equipment. Normally, however, the trip contacts of relay (46) are connected across the operating coil of relay (3a) by an interlock on starting contactor (6) which closes when the contactor opens. Thus, should any trouble arise on the high-tension line while the converter is running, it will be shut down by master relay (3a) but will be left in condition to restart automatically as soon as the high-tension line is again in a satisfactory operating condition.

Each of the feeders is provided with magnet contactors, (40) and (41), which open in the event of an overload by the action of overload relays (51) and (52). When these overload relays open they are held in the open position by a mechanical latch and cannot be closed until the respective resetting coil, (51) or (52), has been energized and has thus released the latch. While in the open position the contactors are shunted by a measuring resistance bridge, the circuit to the mid-wire of the feeder being completed by a contact on (47) or (48) which closes when the relay (47) or (48) is de-energized. This occurs as soon as the feeder contactor (40) or (41) opens, since the operating coil of the relays is short-circuited by an auxiliary contact on the contactors which closes when the contact is open. The resistance bridge is now used to measure the resistance of the feeder. As the load on the feeder is reduced, the voltage-drop across the relay-shunting resistance increases until at a predetermined value the contacts of relay (34) or (35) close, thus completing the circuit of the resetting coil (51) or (52). When the resetting coil has operated, the closing-coil circuit of the contactor (40) or (41) is again energized and closes the contactor, thus restoring the feeder to service. The resistance bridge is dis-

connected from the neutral after a small time-interval by the operation of relay (47) or (48), which is energized through the opening of the auxiliary contact on the feeder contactors. The above arrangement is such that an overload on either of the outers will cause the respective feeder to be disconnected, and only reconnected when the overload has been reduced.

When the demand for power falls to a predetermined value under load, d.c. relays (13) operate to close their contacts and thus energize an underload delay relay (27). After an interval of time, which can be adjusted to be from 3 to 20 minutes, the time-delay relay closes its contact and short-circuits the coil of relay (3a), which opens and de-energizes relay (3). When relay (3) opens, it de-energizes all the a.c. operated contactors and also causes the main oil circuit-breaker (20) to open. The station is now ready to start up again when the demand for power causes the d.c. voltage to drop.

The sequence of operations described above is very quickly performed, the total time from the demand arising to the connection of the rotary converter to the line being seldom greater than 55 seconds, plus the time-lag on the relay. This is a great advance over manual operation, which necessitates synchronizing by hand.

The operation of the station has surpassed our expectations in that its behaviour has been almost perfect since it was first put on load, or rather, put itself on load.

Naturally, numerous adjustments to the relays, etc., have been necessary, but this has been to enable them to meet our conditions of working.

At this point it might be as well to consider in detail the control of the outgoing d.c. feeders, and to consider two possible requirements, i.e. to control a dead-ended feeder and an interconnector fed from another source of supply. With this end in view the reclosing mechanism was designed to be applicable to both.

The feeders are therefore protected with automatic reclosing contactors having overload and inverse time-limit relays. Auxiliary contacts on these contactors are arranged to connect measuring resistances across the feeder circuit when the contactor opens. In the case of a dead-ended feeder they measure the resistance of the system, and if this is above a predetermined value the contactor closes again. If it is not of the requisite value the contactor is prevented from closing; if at a later period the fault is removed, the contactors close and restore the supply.

In the case of an interconnector fed from another source of supply the contactors close only when the voltage of the interconnector has risen to a predetermined value. The operating relay is adjustable over a wide range, and any reasonable conditions can be met with the apparatus as installed.

Various artificial faults have been put on the plant for experimental purposes, but have all been dealt with almost uncannily.

The relays are of substantial construction and we do not anticipate that they will give us any trouble provided that they have reasonable attention.

The fact that we have put a second station in hand on similar lines to the one described rather points to our entire satisfaction. The author would point out that in the station described, arrangements were made to run the plant for traction purposes when desired, the automatic features functioning up to and including the rotary-converter d.c. contactors, following which is a hand-operated throw-over switch, which may be closed on either the lighting or traction busbars, as desired.

The traction feeders are controlled by hand-operated standard circuit-breakers and knife switches. As the station is on a tramway route which several times a year has to handle very heavy traffic, this arrangement is very useful, especially as the station is situated on the top of an incline.

It is of interest to refer to the problem with which we had to deal, and the cost comparison which influenced our decision.

The network between the two stations mentioned was laid at a pre-war cost of approximately £20 858, but as only 40 per cent was available for useful work, due to voltage-drop, a feed into the centre would enhance its value nearly three times. The following five methods were open to us:

(1) To change over the whole of the distribution in the area in question to alternating current, by connecting the d.c. mains across a split single-phase transformer. This would mean that only a single-phase supply would be available and that all consumers' d.c. plant, such as motors, etc., would have had to be replaced by a.c. plant.

(2) To replace the whole of the d.c. mains by a.c. mains, creating a new a.c. system and finally scrapping the d.c. mains; or else to superimpose on the area an a.c. supply. This would mean that there would be two systems in the same area, that the d.c. consumer would be restricted to his existing load, and that the capacity of the d.c. mains would remain at their present value, i.e. only 40 per cent.

The cost of the above methods, coupled with their obvious disadvantages, led to their elimination, and only the three following schemes were considered in detail.

(3) To lay new d.c. feeders from the existing stations to a central point of the system, the feeders to be of sufficient capacity to increase considerably the value of the system.

This scheme would meet the present difficulty but did not allow for further extension or of new distributors being laid down from the point where the feeders fed into the system.

(4) To erect a new building and equip it with manually operated plant with three double shifts of operators.

(5) To erect a new building and equip it with fully automatic plant requiring the occasional services of an inspector.

Alternatives (4) and (5) would allow for very considerable extension to the existing distribution system, as new distributors could be installed as and when required.

Whichever of the three schemes was decided upon, new buildings and plant would be required, as the

present feeding stations were not large enough to allow of more plant being installed, and the existing plant was fully loaded. Therefore, in considering the comparative cost of the schemes, the cost of buildings, rotary converter, manually operated converter and feeder gear has been taken as being common to all.

Considering first the capital cost of alternatives (3), (4) and (5) and ignoring the items common to each, the following would appear to be a fair basis of comparison :—

(3) The cost chargeable is the value of the new cables required from Cobbs Quarry and Rice Lane, together with the cost of laying the same to feed into the network at the position chosen, namely £12 500.

(4) Over and above the cost of laying a short length of feeder out of the station to connect up, the cost would be nil.

(5) The cost of the automatic gear, over and above the cost of the manually operated gear, £1 795, and connecting up feeders as in (4).

No sum has been added in cases (4) and (5) for connecting up the feeders, as the cost would be very little and the annual charge less.

The cost of the high-tension cable in cases (4) and (5) was not taken into account, because in the particular case under consideration the high-tension cable was already in existence and passed the site chosen. In other cases this cost will, of course, have to be taken into account.

As regards the operation of the three schemes :—

(3) would require very little more attention than at present, as the stations were already staffed and inspection would be as hitherto; also the lighting would be only slightly in excess of the existing lighting. The cable losses were neglected; plant losses in converters, being common to all three schemes, were also neglected, so that the only charges on this scheme are the capital charges.

(4) would require three shifts of two men per shift, at £1 285 per annum. As this station would come within the routine of a general inspection, the cost of inspection was ignored. The lighting of the station would cost about £20 per annum, so that the total running charges would be £1 305 per annum.

(5) would require more skilled inspection and a consequently higher rate of pay than the manually operated station, but this would be more than balanced by the reduction in clerical work at headquarters, consequent on there being no weekly wages to be made out and paid to shift men.

The station lighting would be nil, as obviously it would not be required.

The maintenance in the case of all three alternatives has been considered as common to each, although the maintenance on scheme (5) might be slightly in excess of that on either scheme (3) or (4).

As pointed out above, three shifts would be required in the manually operated station (4) although possibly only working 50 per cent of its time, and on this basis station (5) operating on load for 12 hours and being idle for 12 hours per day, with units at 1d. for operation purposes, would cost £93 per annum for energy.

Therefore in this station we should have a capital charge on the excess of automatic over non-automatic gear, and also a running or operating charge of £93 per annum. This brings us to the following actual charges :—

(3) £12 500 at, say, 9 per cent	..	£1 125 per annum
(4) Running charges ..	..	£1 305 „ „
(5) £1 795 at, say, 9 per cent = £162; Running charge = £93		£255 „ „

It would appear from the above figures that, taking the difference between (3) and (5), there would be a saving of £870 in favour of (5) and a difference between (4) and (5) of £1 050 per annum in favour of (5), which represents a considerable saving in the cost of units supplied from this station.

The energy required to operate the station is as follows :—

When idle.—At such times the operating transformer and also the d.c. low-tension feeder contactors, of which there are eight (the neutral switches not being automatic), are alive.

Operating transformer	275 watts
Eight feeder contactors at 180·5 watts each	1 444 „
Total	1 719 watts

When operating.—At such times the operating contactors, in addition to the above, are all closed, making a total of 3 397 watts, and it was on the above figures that the operating cost of £93 was calculated.

In practice it is found that, although the voltage regulator keeps the pressure steady, it does not allow for a rise in pressure with increase in load, i.e. there is no compounding effect. This point in a manually operated station is taken care of by the operator, so that a contactor type of field regulator is being introduced, which is operated from the main ammeter shunts and which will automatically raise or lower the pressure 1 volt for every 100 amperes increase or decrease in load.

As stated above, numerous tests have been applied to prove the ability of the automatic gear to operate under faulty conditions, and its operation has been not only satisfactory but much more accurate and rapid than manual operation, the various relays being able to discriminate more rapidly than the human mind.

The author concludes with the hope that the information given, and the causes and considerations which led up to the decision of the Electricity Department to adopt automatic stations, may be of service and helpful to many engineers who may be hesitating as to the adoption of fully automatic stations.

The thanks of the author are due to Mr. H. Dickinson, the City Electrical Engineer of Liverpool, for permission

to publish the information contained in the paper, and to Mr. L. Breach for his valuable assistance in the preparation thereof.

APPENDIX A.

Relays used in the Operation of the Station.

(1) Under-voltage relay.
(2) Low-voltage and time relay.
(3), (4) and (5) A.C. shunt relays.
(3a) A.C. shunt relay.
(6) A.C. starting contactor.
(7) Polarized motor relay.
(9) Field-reversing relay.
(10) 4 P.D.T. field contactor.
(11) A.C. running contactor.
(12) to (16) 1 250-ampere "C.B." contactor (line and resistance shunting).
(12a) D.C. accelerating relay.
(13) Series underload relay.
(17) 1 P.D.T. knife switch.
(18) Low-voltage and reverse-phase relay.
(19) A.C. shunt relay.
(20) Main oil circuit breaker.
(20a) No-voltage release.
(21) Low-voltage and time relay.
(21a) A.C. shunt relay.
(22) 125-ampere contactor.
(23) A.C. overload relay.
(24) Overspeed device.
(25) Bearing thermostat.
(27) Underload delay relay.
(28) Grid thermostat.
(20) Thermal time-element relay.
(30) Lock-out relay.
(31) Brush-lifting device.
(31a) A.C. shunt relay.
(31d) Brushes down.
(31u) Brushes up.
(32) D.C. reverse-current relay.
(34) and (35) Measuring relays.
(37) D.C. line contactor.
(37) A.C. shunt relay.
(38) Field-current relay.
(40) and (41) Feeder contactor.
(46) Unbalanced phase-current relay.
(47) and (48) Time-lag opening relay.
(51) and (52) Overload relay.
(64) Automatic voltage regulator.

APPENDIX B.

A Short Description of the Principal Relays used in the Operation of the Station.

(1) *Under-voltage relay.*—This is a simple solenoid-and-plunger type of relay in which, when energized, the plunger is drawn up into the coil. This plunger is connected at one end to a pivoted arm with a contact on the other end. The weight of the plunger is partially counterbalanced by a coil spring attached to the opposite end of the pivoted arm. This spring is used for adjusting the voltage at which the relay is required to operate. This type of relay is very sensitive and responds to slight changes in voltage.

(2) *Low-voltage and time relay.*—The main feature of this relay is to provide a short time-interval between the closing of contact (1) and the operation of master relay (3a). It is of the induction type and operates from a single-phase circuit. An aluminium disc is mounted in the air-gap between the poles of the laminated core. The shaft of this disc carries one of a set of contacts, and when the relay is de-energized these contacts are held open by a spring which rotates the disc until the movable contact strikes the top. When the relay is energized the torque overcomes the tension of the springs and the disc rotates until the contacts close. The movement of the disc is retarded by the damping effect of the disc as it moves between the poles of a strong permanent magnet. The time setting of the relay is changed by altering the position of the adjustable stop, which either shortens or lengthens the arc through which the disc must rotate before the contacts are closed. This time is adjustable from zero up to a few minutes. The construction of the relay also makes it a low-voltage relay, since, if the applied voltage is too low, the resulting torque will not be sufficient to overcome the pull of the spiral spring and the disc will not rotate.

(7) *Polarized motor relay.*—This is a d.c. motor-driven relay, the armature of which is connected to the converter pilot brushes. The field is produced by permanent magnets. The motor drives the armature of a magnetic clutch through a series of reduction gears. When the clutch coil is energized, the clutch solenoid housing, which is mounted loose on the shaft, is drawn along until it engages with the clutch armature. Attached to the outside of the housing is an arm carrying the movable contacts. A spring mounted on the shaft keeps the clutch housing normally in such a position that this movable contact is held midway between the stationary contacts (7b) and (7d). The clutch coil is connected in parallel with the motor armature so that it engages and disengages simultaneously with the starting and stopping of the motor. When the proper voltage is applied to the motor it will start in the direction dependent upon the polarity of the armature circuit, and the clutch housing with the movable contacts will turn until contact is made with either (7b) or (7d), the top and bottom contacts. Immediately after the clutch relay is de-energized the clutch disengages and the spring returns the clutch housing to the mid-position. Contact with the clutch coil is made by two small fingers. Another set of fingers (7a) is bridged by a contact strip on the clutch housing when this is in the mid-position.

(18) *Reverse-phase, open-phase and low-voltage relay.*—This relay is very similar to relay (2) except that it is a polyphase instrument. The relay is connected in the circuit so that with normal phase rotation the contacts are held open against the tension of a spiral spring by the torque of the disc. If the phase rotation is changed, the torque will also be in the opposite direction and the contacts will be closed. Also, if an open phase occurs no torque will be exerted. Therefore

a spring will rotate the disc and close the contacts. If the voltage drops below a certain value (usually 80 per cent) the torque will not be sufficient to overcome the effect of the spring when the contacts are closed.

(21) *Time and low-voltage relay.*—This is an exact duplicate of relay (2).

(23) *A.C. overload relays.*—These are the standard induction-type overload relays, and their construction and principle of operation are very similar to those of relay (2), except for a few minor details. The relay is single-phase and the element is wound with a current coil instead of a potential coil. A number of taps (usually 6 or 8) are taken off the small current transformer and brought up to the terminal plate on the index scale. This gives the different current values at which the relay will operate and close its contact. The relay has an inverse time-element up to a certain percentage of the operating load, but for greater currents the minimum time required to close the contacts is practically constant.

(25) *Bearing thermostats.*—These consist of copper bellows connected through a small copper tube to a bulb which is embedded in the lower half of the bearing, where it will be subject to the maximum bearing temperature. The bulb and the bellows are partially filled with a liquid which vaporizes at a given temperature. When the bearing reaches this temperature the bellows elongate owing to the pressure of the vapour, and the contacts are closed, and they remain in that position until reset by hand. Thus, in addition to tripping the lock-out relay, the inspector will have a positive indication as to which bearing was hot. The thermostats operate at approximately 90° C.

(27) *A.C. underload delay relay.*—This is a motor-operated relay and consists of a small induction motor driving, through a spur-and-worm gear reduction, a disc which carries a moving contact. The function of the gearing is to provide a long, definite time-interval between the starting of the motor and the closing of the contacts. Intervals of from 3 to 30 minutes may be obtained. In addition to the slow-closing contacts (27T) there is a second set of contacts (27S) provided, which close momentarily at approximately $1\frac{1}{2}$ minutes after the motor starts to revolve. These are the starting protective contacts which lock the station out if it fails to start within a given length of time.

(28) *Grid thermostats.*—These are practically the same as the bearing thermostats, the only difference being that they operate at a higher temperature. They will reset again as soon as the thermostat cools.

(29) *Thermal time-element relay.*—This consists of a number of bimetallic springs attached to a shaft which carries a movable contact. Current from the secondary of a current transformer in the low-tension side of the power transformer is passed through the bimetallic springs and heats them. The springs tend to unwind and in so doing the shaft is rotated and the contacts close. The element is mounted in a heat-insulated case which is filled with oil. The relay follows very closely the heating of the machine and is very efficient in protecting the converter from damage due to overheating. Mounted in the same case is a low-ratio transformer which gives the correct current in the relays so that it will operate at the most satisfactory point on the calibration curve.

(30) *Lock-out relay.*—This relay has two pairs of contacts and a contact bridge which can make contact across either the lower or upper pair of contacts. In the normal position this contact bridge is latched so that the circuit is closed through the lower set of contacts. When the operating coil is energized the latch is released and a spring moves the bridge until it connects the upper pair of contacts and interrupts the circuit through the bottom pair. Once the relay has operated it must be reset by hand. A small target indicates white when the relay has operated.

(31) *Brush-lifting device.*—This consists of a motor connected through reduction gear to a brush-lifting ring on the converter. A jack-shaft carries four cams which operate four contactor switches. Two of these are limit switches which stop the motor when the brushes are in the correct position, either up or down, and the other two are interlock contacts, one of which prevents the converter from starting until the brushes are up and the other prevents the line switch from closing until the brushes are down. The motor is of the clutch type and does not pick up load until it is almost up to full speed. It is a single-phase motor and the split phase is used in starting.

(32) *D.C. reverse-current relay.*—This relay operates on the moving-coil principle, and is very similar to a millivoltmeter, except that all the parts are heavier and more robust. The relay is so connected that it will close its contacts only when current flows in the reverse direction.

(34) and (35) *Measuring relays.*—These, in connection with a suitable bridging resistance, automatically measure a short-circuit on the feeder when the breaker trips and determine when the conditions are such that the current will not be above a predetermined value when the breakers reclose. The relays are very sensitive to changes in current and are capable of very accurate adjustment.

(46) *Phase-balance current relay.*—This is used to protect the converter against running single-phase. Relay (18) will only prevent the machine from starting up on a single-phase, and in the case of phase failure while the converter is running it would continue to run on single-phase and act as a phase converter and supply three-phase potential which would hold the contacts of relay (18) open. However, with relay (46) in the circuit it will operate when the phase failure occurs, and shut the station down. Then, if the trouble is on the high-tension side, relay (18) will close its contacts and prevent the station from starting until the three phases are normal. If the trouble should be on the low-tension side, relay (18) will not operate, and the station can start up again. As soon as it attempts to start, relay (46) operates again. During starting the contacts of relay (46) are connected in the lock-out relay circuit, so that the station would then be locked out. This is a special polyphase induction-type relay and is operated from the secondaries of the current transformer in the low-tension circuit. If an unbalanced load, such as a phase failure, occurs, the torques produced at the different elements will not be the same and the relay contacts will close.

DISCUSSION BEFORE THE INSTITUTION, 1 FEBRUARY, 1923.

Mr. B. Welbourn: The subject of the paper interests, I think, three sections of the industry, first, operating engineers, many of whom are now troubled with overloaded low-pressure networks; secondly, cable makers; and thirdly, plant manufacturers. I dismiss the cable makers very briefly because they have nothing whatever to lose in the average case, which will require high-pressure feeders. The author's case is a special one where high-pressure feeders existed. Other examples are to be put down and they must involve the use of more cable. I have watched the starting up of the Liverpool substation and on two occasions the rotary converter started up with the wrong polarity. The switches described by the author changed over very rapidly so as to correct the polarity. Last year I examined a fully automatic traction substation near Chicago. In that case the plant was made by the General Electric Company of Schenectady, and was supposed to be the last word in automatic plant. It behaved in the same perfect way as the plant at Liverpool, which is made by the Metropolitan-Vickers and Westinghouse Companies, but both appeared to contain some unnecessary apparatus. I can quite understand that manufacturers and operating engineers will all play for safety while they are launching an entirely new scheme, but I would ask them to combine to collect operating data so that they can determine after, say, five years' experience how much of this auxiliary apparatus can be eliminated, because this is very unlikely to be the last word in automatic substations. Statistics will inevitably show that certain risks can be accepted as good commercial risks. For instance, one would think that at this stage of the art it is hardly necessary to put thermostats on every bearing. I think that the author makes out a good case, from the commercial point of view, for the decision reached at Liverpool. The whole trend of practice at the present time is, in view of heavy labour costs, towards automatic devices. We now have automatic telephones, automatic lifts and so on, and I think that no one need be in any way afraid of the adoption of this principle, because past experience shows that the adoption of labour-saving devices brings more business and thus more work for labour. Up to the present all this fully automatic substation plant is of American origin, although not the whole of it has been manufactured in America. In that connection it would be of interest to know where our own manufacturers stand; for instance, whether they are ready for the considerable market which is sure to come. During the past few days an important order has been placed in one of our northern cities for automatic substations, and it is an open secret that the plant is being made in this country for a number of fully automatic traction substations. As Chairman of the Committee which is organizing the Liverpool portion of the Institution's Summer Meeting this year, I may say that this automatic substation will be thrown open for inspection, and I feel sure that it will prove to be the *pièce de résistance* in that city.

Mr. G. H. Morris: I also have seen the substation described by the author, and I agree with Mr. Welbourn that a reduction in the amount of auxiliary apparatus would be a very great advantage. During my visit the station was started up many times, the average time taken being about 44 seconds. When the rotary converter built up with the wrong polarity it took about 5 seconds longer, but generally speaking there was no fault to find in the sequence of operation. The paper states that the cost of attendants in a manually operated station would be about £1 200 per annum, but this figure is, I think, rather high. I notice that two attendants are allowed for on each shift, but I do not agree that is really necessary in a 500 kW station, and as this station is used on the peak load only I think that three shifts would be unnecessary.

Dr. E. W. Marchant: I, also, have seen the Liverpool substation in operation. The controls may appear complicated on paper, but the apparatus is very sound and strong and the station bears the stamp of good design, both electrically and mechanically. With regard to the increase in utilization of the mains which is brought about by increasing the number of feeding points, if one has a main of uniform section laid between two substations, and one assumes that there is a certain uniform demand for current along the whole length of the main, the maximum value of the permissible current demand is limited by the pressure-drop which is allowed. This, of course, in the case considered will be a maximum at the mid-point between the two substations. If now a substation is introduced at the mid-point between the original substations, the current demand that can be dealt with per yard of main, for the same maximum pressure-drop, will be four times as great. This may be explained, as the author has stated, by the fact that (1), owing to the distance from the substation to the point of maximum pressure-drop being halved, it is permissible to take twice as much current from the substation, and that (2), owing to the introduction of the substation, the number of feeding points to the main will be doubled. Up to the present, the only factor that has had to be taken into account in determining the maximum load permissible on the distributing system has been the pressure-drop, and the automatic substation described has been devised with a view to maintaining the pressure on the mains. When the feeding stations are sufficiently numerous, however, the extent to which the mains will be utilized will depend on their permissible heating. If a very large number of feeding points is introduced it is easy to see that the current density in the mains may be very greatly increased. In this connection it is interesting to note that there is a great advantage, from the point of view of heating, in laying a number of smaller mains in place of a few large ones. In the tests that we made in this laboratory with mains as laid by the Liverpool Corporation, we found that with a main of 0·1 sq. in. section the permissible current density for a temperature-rise of 20 degrees C. was 2 200 amperes per sq. in., whereas for a 0·6 sq. in. main and the same temperature-rise the permissible current density was

only 1 000 amperes per sq. in. It would seem, therefore, that when heating is the predominant factor determining the limit of load that can be put on the system, it is desirable to use a number of mains of comparatively small section, in place of a few very heavy conductors. On economic grounds the case for the automatic substation has been very clearly made out in the paper, and there seems little doubt that, as time goes on, an increasing number of them will be employed on distributing networks.

Mr. L. H. L. Badham: In the installation described in the paper I notice that the machine is tap-started and fitted with a brush-raising device. This, however, introduces a large number of special devices. A method which appears to be less complicated is that employed in the 1 500-volt automatic rotary-converter substations in use on the Victorian Railways. The machines are started with the standard Rosenberg method of self-synchronizing. Each machine has also a small belt-driven d.c. generator mounted on the same baseplate, and this excites an auxiliary shunt winding on the rotary converter during the period of starting, thus ensuring correct polarity This small generator, however, is essentially to provide the necessary source of d.c. supply for the operation of the high-speed d.c. circuit breakers with which these machines are protected.

Mr. W. M. Selvey: We are enjoying, as a heritage of the past, a system of distributing electricity in a form which lent itself in the early days to the simplest and most rapid progress. To-day we have progressed so rapidly that difficulties have arisen, due to the rapidity of the progress. If we turn in another direction to consider the question of traction, the cost of a substation operator has become a very serious item in comparing the relative merits of a.c. traction and d.c. traction. There is no system of mechanism which cannot be improved; in fact, the machine has almost begun to eat the man. The protagonists of the d.c. traction system have produced first of all in America a machine which, as the author says, acts almost more rapidly and more precisely than the human brain. Therefore it is quite natural that when there are certain great immediate advantages to be gained one should adopt a complicated system of mechanism. The idea is not new; many years ago the problem was suggested to Edison, and after considering it very thoroughly he arrived at the conclusion that it was cheaper to employ substation assistants at 25s. a week. Let us consider a little more closely what the author is putting forward. He says, in effect: "I have a system here on which I have spent £20 000, and I am faced with the necessity of doing something more or less immediately. Therefore I can cast a balance sheet, to see which of three methods to adopt." In casting his balance sheet he takes, as the sole criterion, the utilization factor, which is, at present, only 40 per cent with the cables, but which he wishes to raise to a figure not stated. One of his main arguments for taking this as the basis is given in the first column on page 417, where he says: "The more extensive use of domestic apparatus has had the effect of raising the average load taken by consumers from ½ kW to 1 kW for lighting, up to 5 or 6 kW on the average when domestic apparatus such as radiators, cookers, vacuum cleaners, irons, etc., has been installed." I think that is the basis of the paper, and if that is so, by means of his automatic substation the author proposes to perpetuate a system of low-tension distribution. If he has already spent £20 000 on something which has produced ½ kW to 1 kW per head, what is he going to spend on cables if he gets this increased demand? Is he considering what he shall do to utilize the £20 000 worth of cables which he already has and get, let us say, 80 per cent utilization, which would make them worth, from his point of view, £40 000, or is he indirectly going to perpetuate a system which commits him to an expenditure of another £100 000 for cables, without first seeing what would happen if he had taken steps to superimpose an a.c. system? I do not suggest that he has arrived at the wrong solution, but I do suggest that perhaps he has not followed up fully the argument arising from his premises. It is a very serious thing, to my mind, if we are in any case committed to the perpetuation of a system of low-tension distribution. I am strongly seized with what appears to be the uneconomic expenditure on changing over, but I am still more strongly impressed by the difficulties that will arise if we continue to take a new load of heating and cooking on to the old distribution system. I am afraid we are getting very much into an impasse, and I suggest that any system of automatic substations must be properly confined to traction work where the system is direct current, and to those districts which seem to be fairly well saturated and in which there is not likely to be a five-fold increase of load.

Mr. G. A. Cheetham: The author is the first engineer in the country to have the courage of his convictions and to introduce plant into this country which has been used to some extent in America. A brief résumé of the history of the introduction of automatic apparatus into America would perhaps be not out of place. In 1914 the General Electric Company devised a scheme of automatically operating a substation, and they were the pioneers in that respect. They carried on for a few years along the lines they had originally designed, and introduced various improvements. Later the American Westinghouse Company also commenced to supply automatically-operated control gear for substations, but they carried out this scheme of automatic control in a slightly different manner. There are, of course, numerous ways of controlling substations; electro-pneumatic devices or cam-operated switches can be used. The American manufacturers thoroughly tested their scheme of automatic gear before putting it on the market, and that is a warning note that British manufacturers should bear in mind. After all, automatic operation is only a logical extension of the protective and control gear which we have had in this country for a very considerable time, and at last (because this gear has to be in operation daily) it is about to receive some attention in the way of inspection. The engineer hopes that protective gear will operate only on very rare occasions, and in consequence it is forgotten. For that reason many engineers have not a good word to say for it. It is essential that an automatic substation should be thoroughly inspected and that care should be taken of the gear if satisfactory operation is expected from it.

A device illustrating the simplicity of the gear, which in this particular instance is only used for the protection of a traction feeder, actually discriminates between a short-circuit and an overload. That at once suggests complexity, but it is really very simple. An ordinary a.c. transformer is put on to the d.c. main, and the rate of change of current instead of the actual value of the current is measured. A very simple device enabling the feeder to be disconnected immediately a short-circuit occurs, allows the feeder to remain on load to its full capacity in the case of an ordinary overload. With regard to the results of the operation of automatic substations in America, I propose to read a very brief extract from a report read before the American Electric Railway Engineering Association at the end of 1921. It is as follows: "From the operating records available it would appear that automatic operation is more reliable than manual operation. With any property, no matter how well trained the operators may be, there are certain errors of human judgment that must necessarily enter into the operation. In the large centres of population, where the tendency for high labour turnover is more pronounced, there will always be a larger percentage of new operators on the system than in some of the less active, smaller cities. This higher percentage of inexperienced operators will result in more operating mishaps, which are avoided by the use of automatic control. Where interruptions of the a.c. power supply are at all prevalent, the automatic control stands out conspicuously because of the speed with which service is restored." Altogether there are now 400 automatic stations operating in America. With respect to the change-over from direct current to alternating current, one point that is often lost sight of is the usefulness of a d.c. load in enabling a supply authority to keep up its power factor. If direct current is to be retained and utilized to its full advantage, and if copper also is to be utilized to its full advantage, the natural tendency is to distribute a large number of substations over a network at frequent intervals. In the past this has been impossible because of the operating charges, but we can get back to this idea when manual operating costs are reduced, and this is one of the chief advantages of the automatic substation. The automatic substation shows to its best advantage in the cost of control of a certain output distributed over a minimum number of machines. That will be apparent, as a full set of automatic gear is required for each plant unit. In a railway substation the elimination of the no-load running costs is important, especially on a railway where there are few trains running infrequently, as the station can be shut down between the times of running the trains. It should be noted, in addition, that the load efficiency of the station increases, because the station is not called upon to operate until there is some definite load for it. Automatic control is extending rapidly to the control of power stations, especially hydro-electric schemes, and in America many waterways are being harnessed which were previously considered impracticable because of operating costs. There is certainly a very large field of application abroad, and, to some extent, in this country, for automatic hydro-electric stations.

Mr. F. G. C. Baldwin: There are many points in the system described which are of interest to telephone engineers. Judging from what previous speakers have said there appears to be a certain impression that switchgear of the kind described may not be so reliable as manually operated apparatus. A problem that now presents itself to the engineer concerned with the distribution of electrical energy appears to be somewhat akin to one which the telephone engineer has had to tackle in the past 10 years, i.e. as to whether automatic apparatus will function properly, and whether the cost compares favourably with that of manual equipment. So far as the functioning of the apparatus is concerned, I have no doubt at all that, whatever difficulties do arise in regard to design and operation, those difficulties will be surmounted. Such has actually been the case with automatic telephone devices. Experience in telephone working is such that we can now rely upon automatic switches of all sorts to operate with unfailing precision and regularity. In Appendix A the author has given details of a number of relays used in the operation of the station. In telephone exchanges a very much larger number of such relays are used and they give practically no trouble in their operation. We also have thermostats, and machines which are started up each time a subscriber makes a call, and they perform their several functions admirably. The number of relays or similar devices associated with the system described in the paper is 64, while the number brought into operation during the course of one call in at least one automatic telephone system is largely in excess of that number.

Mr. T. W. Ross: I have been associated with the automatic substation question for the past three years, and I can assure those who suggest that the amount of apparatus should be reduced, that the scheme put forward by the author is the result of evolution which has taken place in America, and the amount of apparatus has been reduced as much as possible without impairing the reliability of the gear. The function of certain relays shown in the paper may not be quite clear to members. Certain relays in the scheme are really intermediate steps, and we find in practice that, especially in the more sensitive relays necessary for determining the sequence of operation, it is essential to reduce the current carried by the contacts to a minimum, and we have found that far more reliability is obtained by putting in an intermediate step. Although a thermostat may appear to some to be unnecessary, I can assure them that the thermostats used in this particular station and by other makers of this gear are a real engineering proposition. There is very little possibility of trouble arising when they are used. I agree that it is possible to install too much protective gear, but I believe that certain protective devices which are put into these substations are in themselves a very good insurance, and are worth the little extra cost involved. As regards reliability, I believe that with proper care the majority of relays are very efficient and cause very little trouble. I believe it is a fact that in America the question of starting has developed mainly along the lines of tap-started rotary converters, and I do not think there has been any serious trouble. To my mind, it is a pity to spend money in putting on the end of a rotary con-

verter a pony motor which is only used to start up on occasions. The bogey of tap starting in the past has been the amount of power taken from the mains. Many electrical engineers do not object to putting a 500 h.p. induction motor on the mains, but they appear to think that a tap-started rotary converter will shut the station down every time it starts up. The rotary converter with the present damping arrangement takes very little current in starting. I believe I am correct in stating that a tap-started rotary converter does not average more than 60 per cent of the rated kVA load, and with the present large systems the kick is not felt on the mains at all. With motor-started rotary converters there is no need to raise the brushes, but brush-raising is quite a simple and sound mechanical job and has, to my mind, certain advantages. The brushes are raised by means of a small rod operating on a projection of each brush, which ensures that the dirt which collects there is loosened every time the operation is performed, and that is a decided advantage. I think that those who have had experience with tap-started rotary converters will bear me out that there is no difficulty in regard to the bedding of the brushes. The question of the fixing of polarity has been raised, but I should like to ask what is the good of installing an auxiliary exciter to fix the polarity of the converter when this can be done in 5 seconds by means of a simple, small, mechanically sound relay. The method of pole-slip described by the author is absolutely sure. Are these auxiliary exciters really worth while adopting ? This question of automatic substation control seems to me to have evolved along the lines of automatic telephone exchange control. A certain automatic telephone company have stated that with 196 000 calls there were only seven mistakes. This result is obtained with comparatively delicate relays, and for automatic substation gear, which is much more robust and equally well protected from dust and dirt, we should expect a very much smaller percentage of error. I am quite sure that the automatic substation is a commercial proposition.

Mr. P. J. Robinson (*in reply*): Several speakers have referred to the large number of relays required to operate the plant. This number is, of course, based on the experience gained in automatic operation, and relays have been added from time to time as occasion has arisen. Possibly with more experience some relays may eventually be eliminated. If one is prepared to take risks, relays can be cut out, but as they are of sufficiently sound construction as to be no danger in themselves, it appears wiser to install the relays, the extra cost being an insurance against breakdown. The author is of opinion that bearing thermostats are essential. The estimated cost of operating the station manually has been criticized. This is high at the moment, but as two men are always employed per shift in Liverpool, the cost is determined by the trade-union rates governing a station of a specific capacity. With the present hours of running, two shifts could do the work, but having regard to future requirements three shifts should be allowed. Only 500 kW is installed at the moment, but the station is laid out for extension. The relative advantages of tap-started and self-synchronizing rotary converters are outside the scope of the paper.

Dr. Marchant referred to the heating of mains and suggested a number of small ones run at a higher density. I am afraid that the voltage-drop along these mains would prohibit their use.

Mr. Baldwin stated that more automatic devices are used in an automatic telephone call than in starting up an automatic station; as such devices are necessarily more delicate and used more frequently in the former, it argues well for the safety and satisfactory operation of the station.

Mr. Selvey mentioned the perpetuation of a system of low-tension distribution. It is not quite clear what is meant by this, because whether a.c. or d.c. the distribution system must still be low-tension, and when it is suggested that the average load under certain conditions has gone up from ½ kW or 1 kW to 5 kW or 6 kW the diversity factor of the loads must be taken into account; the former which was purely lighting had a low diversity factor, whereas the latter which is domestic power has a high diversity factor, so that it does not at all follow that the load on the system will increase 5 or 6 times. The actual utilization factor was increased from 40 per cent to 118 per cent, so that the value of the cables was apparently increased from £20 000 to £59 000. Taking a figure, given by Mr. Gillott in his recent paper on "Domestic Load Building," of 65 kW installed and 19 kW actual loading, it is easy to deduce the increase in connected load possible with the above increase in the utilization factor; it appears that about 6·6 times the present observed load could be added before the cables already laid down at a cost of £20 000 would be fully loaded. Thus it seems that a long life has been added to the existing d.c. network without further appreciable expenditure on mains. If at a later date we are forced into relieving this district by other methods, the expense involved will not be much greater than that entailed at the present time.

NORTH MIDLAND CENTRE, AT LEEDS, 6 FEBRUARY, 1923.

Mr. W. E. French: I had some difficulty in understanding the schematic drawing, but the author's explanation of the diagram has made clear to me the operation of the station. The rotary converter appears to be amply protected both with regard to time and overload by contactor (16), and the grid contactors (12) and (12a); the latter are called accelerating coils and appear to be selective relays, which do not allow the rotary converter to come into action should the load be excessive. Do contactors (40) and (41) constitute an additional protection of the converter, or are they an overload protection of the mains as well as a safeguard against an excessive out-of-balance current on either side of the three-wire system? In the latter case their action is, I suppose, instantaneous. In this, as in other schemes for automatic substations, tap-started rotary converters have been employed. I should have thought that the tap-started converter

possesses, from the starting point of view, nearly all the disadvantages a machine for automatic substations could have. First, there is the heavy starting current which such machines demand, corresponding to about 50 per cent of the normal kVA of the rotary converter, with just enough torque to start the machine. Secondly, there is the fear of such tap-started converters coming in with the wrong polarity. Thirdly, owing to the fact that the converter has to start in its own armature field, there is a rotating potential curve with regard to the brushes, resulting in considerable sparking; hence the need of the brush-lifting device. From my experience I should consider such a device to be undesirable and a weak link in the chain. This view is borne out by some records published by Mr. C. H. Jones, Chief Engineer of the Chicago-Milwaukee Railway, who states that about 20 to 25 per cent of all the failures to operate of the automatic substations on his system have been due to the brush-lifting devices. I should have thought that rotary converters started on similar lines used for automatic synchronizing, or cascade converters, would have been distinctly preferable, because they not only avoid all the troubles mentioned but materially reduce the number of control relays and apparatus, simplify the plant and so ensure an easier control of the substation and the d.c. voltage on the distributing mains. As a matter of fact, the cascade converter offers a d.c. machine which can be designed for a frequency lower than that of the supply, and hence advantages of operation and commutation accrue, which machines not constantly under supervision should essentially possess. In the *General Electric Review*, 1918, Mr. Davies deals with five automatic substations, considering two cases for electric traction work. In the first case the trains are running with a 2-hour interval; in the second with a 1-hour interval. The output of the rotary converters in each substation is 300 kW, the daily service is 18 hours and the daily consumption 1 530 kWh in each case on the d.c. side, corresponding to an intake of 1 860 kW on the three-phase side. The total service of all five substations is 90 hours; the standstill period with the 2-hour service is 60 hours, and with the 1-hour train service 38 hours. The no-load consumption of a non-automatic station is given as 15 kW in each case. Therefore, the saving for the automatic station in the first case is 900 kWh, and in the second 570 kWh, corresponding to an annual saving of 328 000 kWh and 208 000 kWh respectively. The daily consumption of a non-automatic station is 2 760 kWh for the 2-hour service and 4 290 kWh for the 1-hour service; this gives a saving of 32·5 per cent and 13 per cent, respectively. These figures point to the conclusion that the instalment of automatic substations for power and lighting service, where the rotary converters are required for a considerable length of time and where the period of idle running of the machines is relatively small, would be a mistake. I do not incline to that view. The problem is rather one of economy of feeders and distributors. The installation of many rotary-converter substations of relatively small capacity must produce such an economy and therefore materially relieve the total operation cost of the whole system. The full extent of such benefit can be experienced only by the use of automatic substations, which eliminate the heavy charges due to personnel. In addition, any reduction of running charges due to avoidance of idle working of the rotary converters is all to the good.

Mr. J. W. J. Townley: The author has explained that this automatic substation has been put in to develop to the fullest possible extent an existing d.c. network. He has considered several alternatives to the existing d.c. system and, to judge from the map which he showed on the lantern slide, he appears to have adopted the best solution of his particular problem, as the conditions are ideal for an automatic substation. He has on either side a manually operated substation, and presumably this automatic converter plant is intended for use on peak loads only. I am inclined to think, however, that the automatic substation will not be developed to any very great extent in this country except for traction work, because if one takes a long view it will usually be found that it is much better to face at once the expense of changing the area to a.c. supply, or, as is being done in several large undertakings, to superimpose an a.c. network on the d.c. system and gradually supersede the d.c. supply. Bearing in mind that the cost of an automatic substation is fully six times that of a static substation of the same output, it will be apparent that a considerable sum is available for the cost of changing-over the system. The automatic substation for general supply networks can only be looked upon as a temporary expedient to prolong the life of existing d.c. networks and for installation in relatively small units. I can hardly imagine the circumstances that will justify an automatic substation containing, say, six 1 000 kW rotary converters. For a substation of this size the cost of attendance is not a great proportion of the total running cost, and I am inclined to think that the manually operated substation will be retained for such sizes. There are certain cases where a partially automatic substation would be desirable, and I have such a substation in mind upon the undertaking with which I am connected. It is a traction substation containing a single unit, and but for the operation of the line circuit breakers there would be no need for an attendant during the time the plant is running. The rotary converter is started up at the same time each morning and shut down at practically the same time each evening. This could be done manually, and with thermostats fitted to the bearings and automatic reclosing circuit breakers such a substation could be run without any other attendance than that required for starting up and shutting down. The capital cost of a semi-automatic substation should be considerably lower than that of the fully automatic plant described, and the existing converters could be used. I have no doubt that some of the apparatus shown will in the future be dispensed with, one of the first items being probably the brush-lifting device. I have recently inspected some tap-starting rotary converters of 500 and 1 000 kW. These machines were started up direct from the a.c. side without the d.c. brushes being lifted. There was no excessive sparking at the commutator and the running up was entirely satisfactory. The actual time taken in the case of the 500 kW set from closing the switch

to the rotary converter being in synchronism was 30 seconds, and the current taken was 35 per cent of full-load current. The elimination of brush-raising and brush-lowering devices will be one step towards simplification. From the published accounts of experience with automatic substations in the United States, confirmed by the author's account of his plant, it would appear that the fully automatic substation is a satisfactory proposal where the conditions are favourable, but the field for the automatic rotary-converter substation lies, I think, in traction work and not in feeding general supply networks, which should, wherever possible, be converted to a.c. supply. There are also many opportunities for the use of automatic gear in static substations, where automatic operation has not, I think, been developed to anything like the extent to which it will be in the future, or to the extent to which it is used on the Continent both for the switching-in and switching-out of transformers and for voltage regulation.

Mr. R. M. Longman: In the case cited by the author the automatic substation provided a good solution of the problem, the deciding factor being that the copper is already in the ground and is being used to only 40 per cent of its capacity. Where the copper is already loaded and where the load will increase, the conditions are entirely different; in this case the best solution would be to superimpose an a.c. distribution system. In large towns a site can generally be chosen near which are shops, offices and factories using a considerable amount of power. By adopting an a.c. system the network feeding the town is much relieved and will probably enable the remainder of the d.c. distribution to carry on for some considerable time. The author has calculated the cost of operation on the basis of three shifts of two men per shift. I have worked a substation containing more than 500 kW of more complicated plant than this, but with only one man per shift. I think that if this substation were manually operated only one shift of one man would be necessary during the load period, as there is a manually operated substation on each side of it. Possibly a second shift would be required for four or six months during the year. What is the nature of the load supply? The time of operation, viz. 45 to 55 seconds, is quite satisfactory, particularly for tap-starting, although Mr. Townley has referred to a case in which a rotary converter was put on the bars in 30 seconds. Are current transformers inserted on the E.H.T. side of the transformer to operate protective gear in the case of a failure of the transformer, or does the machine continue on load until shut down by a drop in the d.c. pressure? In the case of failure of any part of the gear and the plant shutting down, is there anything to indicate to the inspector on his arrival which particular item has caused the shut-down? It is of particular importance that the cause of failure should be discovered quickly, so as to enable the trouble to be rectified, if possible, and the machine put on load again. In the case of a fault occurring on some part of the machine, and the particular piece of apparatus which should have operated failing to do so, is there a second relay which may then operate and so shut the machine down? In other words, is there a duplicate line of defence? I agree with Mr. Townley that we have not given enough consideration to automatic regulation on either d.c. or a.c. systems.

Mr. P. J. Robinson (*in reply*): The author does not agree with Mr. Townley that automatic stations will only be developed for traction work in this country, as there are many instances similar to the one referred to in the paper, which Mr. Townley refers to as ideal. The statement that an automatic station will cost six times as much as a static station is not correct; the author would put it at a much lower rate than this; possibly twice. There appears to be no reason why the life of the d.c. network should not be prolonged (see my reply to Mr. Selvey in the London discussion). The question of tap-started rotary converters is dealt with elsewhere. No doubt, automatic gear will be introduced into static stations feeding into the low-tension system with a view to cutting down light-load losses in transformers.

Mr. Longman has asked if current transformers are inserted on the high-tension side of the transformer. They are shown in the figure on page 419 between the incoming isolating switches and the oil switch. They operate the protective gear as stated in the paper. If a fault on the plant has operated the "lock-out relay" a white disc shows on the relay and this calls the inspector's attention to several relays which alone can operate the "lock-out relay," viz. self-indicating bearing thermostats (No. 25 in the diagram), a.c. overload relay (No. 23), station not functioning in the time given it to complete its operation (No. 27 S), unbalanced phase at starting (No. 46). After overhaul, if it is not clear what has happened, the gear will be operated until it ceases to function, at which point the trouble will be located.

Mr. French asks if (40)–(41) act as protective gear to the converter. They do not directly, as they constitute the feeder protective gear. Their action is instantaneous. The figures which he gives regarding saving on automatic stations which have considerable idle periods are very interesting. They are in agreement with the author's conclusions.

NORTH-EASTERN CENTRE, AT NEWCASTLE, 12 FEBRUARY, 1923.

Mr. H. W. Clothier: The author says that British engineers have fought shy of fully automatic control, so Liverpool appears to have taken a bold step. I suggest that it has been not so much shyness as cool calculation on the part of British engineers. It is not that they did not think of it. Nearly 30 years ago some automatic gear was designed for switching in and out banks of transformers for use in this town by the Newcastle and District Electric Lighting Co. It is almost as long ago that the remote-started and remote-controlled automatic substations were installed at Hull and elsewhere on a high-tension d.c. transmission system. At Hull to-day there are 20 fully automatic substations distributing direct current. Is it that the

economy in putting down small d.c. substations has not been proved, or that in their wisdom British engineers have found greater economy in a.c. distribution? It cannot be for want of skill in the manufacture of automatic apparatus in this country. I am sure that there is no need to search America or Switzerland for designers and manufacturers of automatic electrical devices. There has, in fact, been a surfeit of them in this country; no sooner does one automatic device appear than others just as good, if not better, are produced. However shy the users may be, there is no shyness on the part of British manufacturers. I am not quite convinced that the cost comparison is correct. It seems to me that six attendants at £200 per annum is an extravagant use of men for running a little substation of 500 kW. In schemes (4) and (5) on page 422 the capital cost of the plant in not included. If the substations were made larger the proportionate cost of the attendants' salaries would go down and that of the automatic gear would go up. Has the author made comparisons over a broader range of plant capacity? I feel sure that there have been some good reasons for the comparative scarcity in demand for automatic substations in this country. Could anything be more demoralizing for two men than to sit in that little substation day in and day out with practically nothing to do but watch a few instruments and occasionally turn a handle? If only for their sake let us have the automatic substation. It may deprive a few of that monotonous prospective occupation, but it will cultivate a better type, a skilful operating engineer whose mind can quickly grasp a diagram and whose fingers are adept in the adjustment and connection of relays. The lot of an operating engineer will not be bereft of activity. As a test for the type of man, consider carefully pages 418 and 419, on which are given the sequence of operation of relays, contactors, auxiliary switches, etc. If a man can pass the point where the "converter will start" without heaving a sigh of relief, he is a very clear-minded man and a promising operating relay engineer. The expression "almost perfect" on page 421 shows that however little it may be there may be yet some improvement necessary and some work to be done. A good case may be made out for the use of motor converters in automatic substations in the future, due to the ease of starting-up and synchronizing. The crux of the whole problem is, of course, robust relays in distinction to instrument work.

Mr. R. D. Spurr: I agree with the author as to the utility of the fully automatic substation, but we have not, I think, quite appreciated its proper sphere of operation on a d.c. 3-wire network. Automatic substations were first used in the United States as booster substations for the purpose of maintaining a straight-line voltage on long lengths of suburban tramways, and by applying them in a similar way to large, straggling d.c. 3-wire networks we shall attain the desired result. At the present time many d.c. networks are, as the author states, loaded to 40 per cent of their full capacity and, owing to the demands for current in residential areas occurring at times which do not correspond to the usual industrial load demands, we are faced with an interesting problem in voltage regulation exactly similar to the problem solved in the United States by the automatic substation. Assuming a network supplied from several automatic substations as well as from a manually operated substation, the failure of the latter would probably shut the supply down altogether, but the failure of one automatic unit would not be seriously detrimental to anything, except that the voltage regulation would be bad until the plant was in service again. I feel sure that the voltage regulation as a whole would be better than it is with manual operation. The d.c. feeder switchgear seems to be very complicated. My experience has been that a good substantial fuse gives the best protection on low-voltage circuits; it has its own natural time-lag and is generally more reliable in every way than a circuit breaker which is very seldom used, never inspected and which, in consequence, fails to operate at the critical time. Three or more parallel d.c. feeders can be quite safely operated with fuses at both ends, and the chance of a faulty feeder not clearing properly is very small. The labour question with manual substations is an acute problem. In the majority of cases one man per shift is sufficient to operate the plant, and two shifts per day will allow the plant to be available when it is most wanted. In fixing upon one man per shift in a substation it must be understood that he confines his attention to operating the plant only, which can be and is done with perfect safety. Under no circumstances must the substation attendant be called upon to undertake any duties requiring the opening of E.H.T. cubicles; this should always be performed by an authorized person who is not a substation attendant or regularly employed as such. In most cases where an additional feeder is required it will be found that an automatic substation will cost about the same as the feeder, and a manually operated substation about twice as much. The automatic substation will supply the network with twice as many units as the proposed new feeder, and to make a manual substation a reasonably paying investment it must turn out twice as many units as the automatic plant. The losses in d.c. feeders are very seldom taken into account, but it will be found that with a long 0·5 sq. in. feeder never more than 50 per cent loaded, the actual watts lost are approximately equal to the total losses in a 500 kW automatic plant. The automatic substation will undoubtedly lengthen the life of many d.c. networks in residential areas and will enable them to meet the domestic loads which are gradually increasing.

Mr. W. T. Dalton: The author states that "it has been left to Liverpool to lead the way" in the adoption of the fully automatic control of substations. In 1920 the Newcastle Transport and Electricity Undertaking, when preparing designs for a traction substation in one of the outlying districts, provided for its fully automatic operation, but at this date prices had reached the high-water mark and the cost of the switchgear alone was £4 000 for 700 kW of plant, and as the substation was only to be worked on two shifts this figure was considered prohibitive. The scheme was therefore abandoned, not for want of confidence in the reliability of this form of control, but due to cost only. Has the author considered the use of telephonic communication

between the substations and the generating station? It would appear that if suitable search coils, or a loud type of sensitive transmitters, were placed adjacent to the machines, with corresponding receivers at the supply end, continuous indication would be given as to whether the plant was running normally or otherwise, and short-circuits, or the noise from chattering brush-gear as the results of a flash-over damaging the commutator, could be detected, thus enabling the staff to keep in constant touch with these unattended substations. Is there any provision for heating these substations? This may appear to be quite unnecessary, but will not some of the switchgear, if not protected against moisture due to climatic conditions, suffer in the course of time? The conditions in America are more favourable, the climate being much drier than it is in this country.

Mr. B. H. Leeson: Manual operation consists of performing a sequence of operations in such a manner that the plant is not subjected to conditions likely to damage it, and therefore the problem of designing an automatic substation equipment as an alternative is chiefly one for the switchgear engineer experienced in the design of protective apparatus. Automatic control should prove very efficient in running costs, particularly in the case of two or more machines, as the maximum output can be obtained from them, based on their thermal condition instead of by ammeter readings as in the case of manual control. Automatic equipment can discriminate where manual operation alone cannot. The automatic reclosing of a feeder circuit-breaker taking place only when its load will be within a prescribed limit is an example of this, and it protects the plant against unnecessary wear and tear. Protection for the machine against excessive overload, including short-circuit conditions, has received a great deal of attention by manufacturers of switchgear, and high-speed circuit breakers have been evolved and seem bound to take a very prominent position, particularly on traction schemes. The question of inserting resistance in the d.c. circuit to limit the output of the machine has been discussed at great length in the American technical Press, but I consider that its use on our systems will not be justifiable in many cases. I should like to have the author's opinion upon this question. The electrification of main-line railways offers a large future for the automatic substation. A typical scheme would consist of a chain of substations situated close to the track and fed from E.H.T. mains running alongside the permanent way. The d.c. feeder cables to the track would be short, as adequate protection to the machine against flashing-over troubles could be obtained by the use of reactance high-speed circuit breakers of the reclosing type. Thus a good voltage-distribution would be assured with a minimum cost of operation and capital expenditure on copper.

Mr. T. W. Ross: Some of the previous speakers have referred to converter substations in this country running unattended, but there is a decided difference between such substations and automatic substations. An automatic substation should do more than simply start, stop and parallel a rotary converter. The properly designed automatic substation should, in addition, be capable of anticipating any faults which may arise either inside or outside the substation, and of dealing with them more intelligently than the average operator. It is here that a fully automatic substation equipment differs from a so-called automatic substation, and intending purchasers would be well advised to study any scheme carefully and find out its limitations. The automatic substation was first developed in America. I have had the advantage of access to the inner history of its evolution and I would suggest that there is more in the design of these equipments than would appear at first sight. My company decided first of all to install an American equipment before launching out on our own designs. The experience gained has been very valuable and after exhaustive tests and experiments we now feel that we have perfected our own apparatus. I would strongly advise other manufacturers to try out their gear thoroughly before putting it on the market. To show the extent to which the automatic substation is being developed in America, I would mention one equipment which is being put into operation by the Westinghouse Company, in which 35 000 kW of rotary-converter plant is being controlled from a central office by means of automatic telephone relays. One pair of telephone wires connects the central office to each substation, and by using the ordinary telephone dial switch the machines can be controlled as required. This pair of telephone wires not only starts and stops the machines, but also indicates the load on each machine. The control engineer can thus see at a glance the load condition on the whole system and arrange to run his plant to the best advantage. This particular company claims that the increased distributing efficiency obtained is worth the large capital outlay.

Mr. A. T. Robertson: Arrangements are made to ensure that the converter has the correct polarity when supplied with current from the starting taps of the transformer, but there do not appear to be any provisions made to prevent the converter slipping a pole and so being unsuitable for putting on load during the operation of the relays between the opening of contactor (6) and the closing of contactor (11). Does the operation take place so rapidly that there is no possibility of a pole being slipped?

Mr. P. J. Robinson (*in reply*): With regard to Mr. Clothier's remarks, I have not attempted to prove that automatic switching has not been in operation for many years, for that point is indisputable, but there is a distinct difference between automatic control and fully automatic control. In the former the human element is the cause of the operation, whereas in the latter the human element does not appear except at its inception. The 20 stations at Hull come under the former heading. It is also indisputable that the first fully automatic stations were developed in the U.S.A., however much it hurts our pride to admit it. That we have engineers capable of improving on, and developing what has been produced is beyond doubt. As regards economy in a.c. distribution the paper deals with a particular d.c. area which was in existence, and does not suggest its adoption for new work. Mr. Clothier refers to the expression "almost perfect"; in this statement he is correct, for to accept any piece of

apparatus as "perfect" is very foolhardy, and the author admits most readily that there is great room for improvement and a large field for investigation into the various elements which go to comprise a fully automatic station.

In reply to Mr. Spurr the question of fuses as against contactors received considerable attention, the contactors being decided on in view of the possibility of a temporary fault shutting down one section of the network permanently if fuses were adopted, and only temporarily if contactors were adopted.

It is interesting to note from Mr. Dalton's remarks that Newcastle contemplated a fully automatic traction station in 1920 and it is to be regretted that it was found impossible to carry the scheme through, as useful information would have been available to-day in regard to operating charges. As regards the heating of the substation, the operating transformer being situated under the high-tension cubicle is sufficient to keep it free from moisture. With this object in view, the transformer was put in the position stated.

The author appreciates Mr. Leeson's comment as regards collaboration between the engineer responsible for the lay-out of the scheme and the designers of the apparatus to be used. This is essential to obtain the best results, the engineer obviously not having all the sources of information at his disposal that the designer of a large firm of manufacturers can command.

If Mr. Robertson will refer to another section of my reply he will notice that the actual time required to correct the polarity is 4 seconds, i.e. the time of starting up if the polarity is correct is 41 seconds, and, if the polarity is incorrect and has to be corrected, 45 seconds.

Mersey and North Wales (Liverpool) Centre, at Liverpool, 19 February, 1923.

Mr. J. S. Peck: As I am not familiar with the actual details of construction of automatic substation apparatus, I shall not attempt to discuss the paper in a technical way. For a long time I have watched the development of the automatic substation in America. Some 18 months ago when I visited the United States, I took occasion to investigate the matter more closely. I visited several installations and discussed engineering features with the designers and found that both designers and operators were most enthusiastic as to the future of the automatic substation and the enormous developments which were likely to follow. After returning to this country it was arranged that an engineer from the Westinghouse Company should visit Great Britain in order to advise us as to the possible field for automatic substations here, and also to discuss the question with operating engineers in this country. This engineer, Mr. Wensley, succeeded in convincing many engineers here that there was a very promising future for the automatic substation, and I think he confirmed the opinions previously formed by Messrs. Dickinson and Robinson with regard to the advisability of installing such stations at Liverpool. In entering a new field where the apparatus is as complicated as is the case with the control for automatic substations, we deemed it advisable to take the fullest advantage of the experience gained by the Westinghouse Company, and the first equipments installed in this country were manufactured at Pittsburgh. Since then we have manufactured one complete equipment at Manchester and are now in a position to produce such equipment on commercial lines. We have thus been enabled to avoid many of the difficulties which are almost invariably encountered by any firm starting to develop a line of apparatus without having had previous experience in its operation.

Mr. J. H. Williams: I should like to ask the author whether the method of feeder protection with automatic reclosing contactors arranged by means of auxiliary contacts to connect a measuring resistance across the feeder circuit when the contactor is open, is as good as the alternative arrangement using a contactor which closes on a fault a definite number of times with a time-delay in between the closings and which is then locked out. The first method leaves the feeder always alive, a disadvantage on a traction system as the trolley wire is alive. We are actually fitting recorders on some of the automatic substations which we are installing, to record the operation of the various relays, etc., and we hope to get some useful information thereby. In one corporation system where the substations are worked with standard rotary converters and switchgear, the plant is started up and the substation run without attendants, and there has been practically no trouble. Automatic substations behave very much better than manual substations under fault conditions. Quite a number of automatic substations are now being manufactured in this country for tramway and railway load, and I do not think that the author is correct in saying that this is the only three-wire station in the world. I believe there are very nearly 20 in the United States. We do not like the method of starting up the rotary converter by means of tappings and a field-reversing relay and contactor, but prefer induction-motor starting with a separate exciter.

Mr. S. E. Povey: The use of automatic substations is particularly interesting from a railway traction point of view, as a means of reducing running charges. They appear to be applicable in certain instances, e.g. (1) on sparsely loaded sections; (2) to meet increases of load on existing sections; and (3) to meet loads during morning and evening rush hours. When used as on item (1), by shutting down the substation plant between trains the light-running losses are greatly reduced. With reference to items (2) and (3), particularly for suburban and inter-urban services, the traffic requirements demand almost twice the seating accommodation during the two morning and evening rush hours than during the remaining hours of the day. During these rush hours it is necessary to maintain the schedule speed because of the small headway between trains. Therefore in laying out a section due allowance must be made for the voltage-drop on the high-tension feeders, and particularly on the third

rail, produced by these peak loads, so that the average voltage at the train is sufficient to enable the motors to work the train to schedule times. When these conditions are met it is obvious that during the light hours of traffic the system is under load. Again, even during "light traffic" hours, the large peak loads taken when starting a train, and not the average hourly load, in some cases govern the number of rotary converters which must be on load at a substation. The use of automatic substations will enable intermediate substations to be shut down during the "light traffic" hours without the average voltage at the train being too low to maintain the schedule, and by concentrating the load on a smaller number of substations the light running of all rotary converters will be greatly reduced. In the matter of control the subject appears to be quite different on a railway system than on a lighting and power system. On the latter the load is comparatively steady and the voltage on the network is not rapidly fluctuating. The minimum-voltage relay is therefore quite suitable for governing the starting up of the Walton or similar substations. However, on a traction system the heavy starting current causes large fluctuations of voltage on the third rail. While the operation of a voltage relay can be set to depend upon the average voltage, the train service is not symmetrical, and therefore the voltage control for starting an automatic substation does not appear to be fully suitable. The load on an electric railway follows the time table and is very definite and therefore, except in the event of the failure of an adjacent substation, the control of starting up and shutting down an automatic substation should be by time. Distant control from an adjacent substation would, however, appear to be advisable fully to cover the conditions. It is noted that the overload setting of the d.c. line circuit breaker is controlled by the "rate of rise in current value." I would draw the attention of designers to the heavy current taken in starting a main-line electric train, and would point out that the current taken on the first series or parallel notch may be from 1 800 to 2 500 amperes. The amount of current passing to a short-circuit will in some cases be less than these values. Again, I do not agree that the proposed method of measuring the resistance of the track before reclosing the d.c. feeder circuit breaker is satisfactory. The current taken by the brake pump motor, the heating and lighting of trains and stations, and the resistance of the fault, will have to be taken care of. It is not advisable to have any voltage on the track in such cases, as a motorman might have to carry out emergency repairs or adjustments near the third-rail shoes, etc. Also, the reclosing of a d.c. feeder circuit breaker three times before finally leaving it out is not to be recommended for a railway system. It would appear that because of important junctions, and when the train loads require the installation of three or four rotary converters, some substations will still require to be manually operated, and the d.c. feeder circuit breaker in adjacent automatic substations should be reclosed only when the voltage has been restored to the section by the manually operated substation. Automatic control of a substation equipped with two or possibly three machines would appear to be economical, but when four machines are installed manual operation is more economical. The possible economies by the use of automatic substations are to be welcomed as an item on the right side of the balance sheet when considering railway electrification.

Mr. J. H. Collie: Is it possible to use automatic substations on a railway system employing regenerative control? If so, what arrangements are made to keep the line open to receive the current generated by the motors during braking, which in some cases amounts, I understand, to 10 per cent of the power supplied, seeing that the substations would automatically shut down on the load being removed?

Mr. G. E. Swift: The paper disarms criticism in that it is purely a description of a fully automatic substation, and the fortunate circumstance of the substation being required on the route of the E.H.T. main no doubt went a long way towards the decision to erect a substation in preference to laying down more copper. As the substation has only recently been put into operation it is perhaps too early to describe and criticize it, but the fact that the installation operates with the discrimination described is most important. The substation has only one rotary converter installed, and having regard to the number of automatic apparatus it would appear essential to have duplication. If a second rotary converter were installed, and both were running on load, in the event of the load being reduced would one cut out or would both continue to run on divided load? If the substation has rendered idle a low-tension feeder, to what use will this be put? This would appear to have some effect on any basis of comparison. A comparison of the advantages to be gained by the use of automatic installations as against the laying down of additional copper would be welcome. It would appear that the conditions that a fully automatic substation has to fulfil do not obtain in many districts, and in many cases the consumers' habits are such that their requirements can be anticipated and met by a non-automatic substation with the usual protective devices, left to run without attention. Two such substations, each of 500 kW capacity, are in operation in Chester. They are installed adjacent to engineering works, the electricians of which start up and shut down the rotary converters when instructions are received by telephone from the generating station. These substations have been in daily use for over 12 months and have successfully met faults on both the a.c. and d.c. sides, while the operating costs for both do not exceed £50 per annum.

Mr. P. J. Robinson (*in reply*): It is very encouraging to learn from Mr. Peck that in future the apparatus required for automatic stations can be entirely produced commercially in this country and not have to be purchased abroad.

In reply to Mr. Williams, for the particular work required of the feeder contactors I think that the relay which discriminates between a bad fault and a high-resistance fault is to be desired. The fact that the feeder is alive is immaterial, as, of course, if the feeder fault has a low resistance the voltage on the feeder will be very small. If the voltage rises, then the fault

has been removed and the contactor will close without delay and so restore the supply. If it is desired to work on the feeder, the control switch in the automatic station is opened and so makes the line dead. Stations which are started by hand and left on load must, of necessity, be very inefficient, owing to the light-load periods, and also it must be borne in mind that a large city may have many stations dotted about over large areas, which would make it very expensive to keep a staff for starting up and shutting down. I have referred elsewhere in my reply to the relative merits of tap-starting as against other methods of starting.

The majority of the comments made by Mr. Povey are outside the scope of the paper, but at the same time they are very interesting and instructive, and I have no doubt that all the points could be satisfactorily met in practice. It is distinctly worth noting that railway engineers regard automatic stations so favourably, both in this country and abroad, and I feel sure that in the near future there will be many operating on that class of work.

In reply to Mr. Collie, the station under discussion does not, of course, meet the case of regenerative control, but there appears to be no insuperable difficulty in meeting the case if it arises on railway work.

Mr. Swift is correct in his surmise that the E.H.T. supply being so near the centre of the load did help in the decision to erect a substation in the particular position chosen, but it did not materially influence the decision to erect a substation, as it would be a cheaper proposition to lay high-tension as against low-tension cables, which latter would meet the requirements only for the time being. The station is at present equipped with only one converter with automatic gear, but arrangements have been made for extensions in the future. The automatic gear will operate to cut in the second converter when the first is loaded up, and to cut it out again when one converter can deal with the load satisfactorily. The author has dealt with the question of stations started up and left to run. The two cases mentioned by Mr. Swift are not relevant to the point under review; obviously if one can get someone else to start one's station it is the cheapest method to adopt; also, the supply to, and the protection for, a bulk load must be dealt with in a different way from a general supply.

South Midland Centre, at Birmingham, 21 February, 1923.

Mr. R. A. Chattock: The author has described the difficulties that have to be met when a d.c. distributing network fed from a central station or substation becomes heavily loaded. I agree with him generally in the principle that has been applied at Liverpool to solve the problem. I should, however, like to suggest some other points of view which I think would tend to simplify and cheapen the proposition. The author states that only from 30 to 40 per cent of the copper in the long low-tension feeders is available, owing to the voltage-drop. He has surely overlooked the possibility of boosting at times of heavy load on the long feeders; by this means such feeders can be run up to 70 to 80 per cent of their capacity of 1 000 amperes per sq. in. I quite agree that a.c. four-wire distribution is simpler and cheaper to install from a distribution point of view; it is, however, not so good from the consumer's point of view. There is no stand-by possible, as there is with a storage battery in the case of direct current, and this is a most serious limitation in a densely populated and business centre. Again, alternating current is not nearly so useful for the small domestic motors, such as vacuum cleaners, washers, fans, etc. I quite agree, therefore, that Liverpool was wise to discard that way of overcoming its difficulties. Of the other three methods suggested, the laying of further d.c. feeders from the old or new centres is not justified when compared with automatically controlled substations. Where manual control is used, the high labour costs necessitate the installation of plant of large capacity. Automatic operation, however, allows the efficient use of plant in small units. The smaller the better, down to 50 or 100 kW, and this is where I join issue with the author. By adopting rotary converters for this purpose he has introduced what, in my opinion, are unnecessary complications. He is obliged to use units of plant of not less than 300 kW, owing to the high cost of the discriminating and protective gear, and this means that he must employ a certain number of d.c. feeders to get the output distributed in the network. In other words, he cannot quite approach the simplicity and cheapness of the a.c. system. I think that if he had adopted the plain induction motor-generator he would have greatly simplified the control though the efficiency would not have been so good. I think that this, however, would have been justified as such plant would cut in only at times of heavy load, and this effect would not be felt to any great extent. In order to approach the a.c. system, smaller units of plant are required, which can be installed at more frequent intervals and fed straight into the d.c. network. With a view to meeting this condition I have been experimenting with the mercury-arc rectifier. A 225 kW rectifier of the Brown-Boveri steel cylinder type has been installed across the outers of a d.c. network in the Harborne substation for about 18 months, and for the past 12 months has been working absolutely automatically, the substation being visited only about once a week when the apparatus is working alone in parallel with a storage battery. I should like to assure the author that there are other British engineers, notably in Birmingham, who are not afraid of automatic control. I am so satisfied with the behaviour of the mercury-arc rectifier that I have now installed two 25 kW automatic glass-bulb rectifiers of the Hewittic Electric Co.'s make across the two sides of another d.c. network. These are now functioning quite satisfactorily, and I am proposing to develop the supply to the outlying thinly populated districts in Birmingham by means of this type of apparatus arranged for automatic operation, i.e. it will cut out if the extra-high-tension supply fails, and cut in again

when it is restored, faults on the d.c. network being controlled by fuses or circuit breakers. Such a system is directly comparable with an a.c. system, with the exception of the cost of the rectifier itself and a slightly larger substation building. Small substations can be installed wherever required to maintain the pressure over the network, and at times of light load certain of the substations can be arranged to cut out automatically. The necessary controls are quite simple, and are far less in number than the formidable list of 41 controls set out by the author in Appendix A as being necessary to control a rotary converter. I hope to be in a position shortly to describe in detail the controls that we have installed on our rectifier at Harborne.

Mr. F. Forrest: The author has not referred to the running hours of the automatic substation, nor the average load factor, so that we are unable to judge whether the choice of a rotary converter for use in this substation was justified. The rotary converter is the most difficult of all substation converting units to adapt for automatic control, but it is a highly efficient machine. If, however, the running hours are short, a less efficient machine which would require a cheaper automatic equipment for controlling it would be preferable. I presume that the rotary converter is a reactance-controlled machine, the voltage being varied by altering the field current. If this is so the question of power factor will become rather serious, as the author states that the machine is put into service when the voltage of the d.c. network is low, and this may coincide with a time when the voltage of the a.c. supply to the substation is higher than normal. Under such conditions the field current of the rotary converter would be reduced very considerably, and also the power factor. In fact the rotary converter working under such conditions may have a much worse power factor than the ordinary induction motor. The schematic diagram does not indicate how the change-over to traction supply is effected, but I presume that this is done by means of a tapping on the high-tension side of the transformer, which in turn will require a second extra-high-tension oil switch. The paper describes a highly ingenious arrangement of automatic relays which, however, because of their complexity will induce engineers to turn their attention to types of substation plant for automatic working which will necessitate fewer and simpler pieces of control apparatus, such as the induction motor-generator or the mercury-vapour rectifier.

Mr. G. Rogers: It is certain that with any type of automatic substation plant some risks have to be taken. The engineer who purposes to equip such substations must face these risks and assess them at their proper value. The failure of a fuse (of which I imagine there must be many to protect the various automatic relays) renders the plant inoperative and may involve a serious failure of supply. In cases where the substation is designed to feed into an existing network (such as in the case described by the author) or where there is a battery stand-by, the risks are minimized and can be faced with a greater degree of confidence. No engineer will install automatic converter substations for the sake of doing so; there must be a distinct saving of costs. In the case in point the author claims a distinct saving in the running costs, but it must be pointed out that in the case of the manually operated substation the total running charges of £1 305 given on page 422 could be reduced. In the case of a boosting substation of this type the machine would come into service only for the duration of the peak, which may be, if it is an industrial load, between the hours of 8 a.m. and 6 p.m., or, if purely a domestic load, on the evening peak only. In the latter case one shift only would be sufficient to operate the station, or, if the former, two shifts per day would meet the case. I should be glad if the author would give the total capital cost of this substation. I estimate that the cost of the rotary converter and the automatic switchgear was approximately £13·4 per kW. Automatic converting plant of the mercury-arc rectifier type could be installed for much less than this figure, i.e. about £8·9 per kW. I believe that there is a big scope for automatic substations for boosting purposes and for supplying outlying districts, but it will not pay to install them in cases where the supply can be given by means of new feeders run only from existing stations. Within a radius of 1 000 yards d.c. feeders could be laid to supply 500 kW at a total cost, including the boosters to enable full use to be made of the copper, less than that of installing an automatic converter substation such as described in the paper. I shall be glad if the author, in his reply, will give the following information: (1) The number of times per week it has been found necessary to visit the substation for inspection purposes; (2) the average daily machine load factor over 24 hours; (3) whether the converter can be started up by manual operation in the event of the failure of any part of the automatic switchgear; (4) whether there is any means provided to indicate outside the substation that the machine is in or out of service; (5) how the output from the station is measured, and what records are kept. Referring to Mr. Chattock's remarks and description of the automatic mercury-arc rectifier substation which we have had in operation for the past 12 months, I propose to describe the operation of this gear by means of a lantern slide, from which it will be seen that the arrangement is comparatively simple and involves the use of only 14 relays.

Mr. W. E. Groves: The ingenuity of the relay equipment of the automatic rotary converter substation must be admired, and, as the author testifies to its satisfactory operation, there is only left the question as to whether other means to the same end, involving less complex control, are not available. Such alternatives have been mentioned by previous speakers in the discussion. The smaller the amount of auxiliary apparatus necessary, the greater will be the range of application of the automatic substation from considerations of reliability as well as cost. It is certain that there is a very useful field for automatic substations to assist existing d.c. networks such as are dealt with by the author. Whether it will pay to employ them, as against laying down additional copper and feeders, is not difficult to determine. The author, however, neglects cable losses in making his comparison. This is hardly fair to the automatic substation, as these losses

must vary inversely with the money spent in copper. It must therefore be assumed that he has made sufficiently liberal allowance in his estimates to justify such losses being ignored. The alternative of boosting has to be considered. This would be inadmissible except for dealing with peaks of short duration, and would not therefore apply to the 12-hour runs mentioned, but it is bound up with the question of cable losses. The author seems to suggest that he would have preferred to deal with the situation by substituting alternating for direct current, and his reasons for not doing so are convincing. In most large towns there is a zone where direct current is the right system because the loads are concentrated and direct current has certain advantages both from the consumers' and the distributors' points of view. Alternating-current distribution finds favour with the mains engineer because it reduces the liability to faults, and its adaptability to transformation must always commend it, but the development of automatic converting or rectifying substations will enable d.c. distribution to be extended into areas where this system would otherwise be impracticable, and the homogeneity of the supply system as a whole will be increased.

Dr. C. C. Garrard: I think that the author has made a very good case for the use of automatic substations for the purpose in view. I have inspected the installation at Liverpool, and I should like to congratulate him on the scheme and lay-out which he has adopted. It would be interesting to have a little further information regarding the grid. Could the author state the voltage-drop across this grid resistance with the full current passing through it? As far as I can judge from the paper, the grid resistance is of very low ohmic value; such being the case, I fail to see how it limits the current from the substation in the event of a dead short-circuit. Of recent years the use of economy resistances in contactor design has been as far as possible obviated, and as the contactors used are operated by alternating current I should have thought economy resistances unnecessary. Their use seems rather a retrograde step. With reference to the extra cost of the automatic gear, which is given as £1 795, may one take this as being the minimum extra cost for the smallest possible automatic station? I should also like to raise the question of the use of a tap-started rotary converter. I cannot understand why the latter has been adopted. The motor-started rotary converter seems very much more suitable for automatic operation. With the motor-started machine neither brush-lifting gear nor a pole-slipping device is required, as one can always rely on its synchronizing with correct polarity if auxiliary chokers are used. Its adoption would result in considerable simplification of the automatic switchgear. I should be glad if the author would state if there is any particular reason why a tap-started machine has been adopted. Also, it would be interesting to know whether the addition of a second or third rotary converter in the substation is contemplated when the load warrants it, and whether the automatic gear will deal with the problem of starting up one machine after another, according to the load demand, and shutting them down in a corresponding manner. In the upper portion of column 1, on page 421, the author states that the sequence of operations seldom occupies a time greater than 55 seconds, plus the time-lag on the relay, and that this is a great advance compared with manual operation, which necessitates synchronizing by hand. According to my experience, however, a self-synchronizing hand-operated rotary converter of this size starts up in less than half of 55 seconds. I do not mean by this, of course, to argue against the use of automatic gear under such circumstances as set forth by the author. The great point about the automatic gear, in my opinion, is that it saves labour charges, and renders the installation of substations economically possible in cases where it otherwise would not be.

Mr. J. A. Cooper: At a recent discussion before the South Midland Students' Section I was impressed by the number of members who had had experience of faults on protective devices. I should like to ask, therefore, if the author has experienced any faults on the relay apparatus, and, if so, how many. With reference to the Harborne substation, I suggest that it would be an improvement to fit a relay to the vacuum pump so that the rectifier vacuum might be kept always at its working value and no time be lost by pumping up before switching in.

Mr. P. J. Robinson (*in reply*): In reply to Mr. Chattock, direct current certainly seems preferable to alternating current from the consumer's point of view, but for outlying residential districts, thinly populated, there appears to be no case for the former from the supply undertaking's point of view; these districts if formerly supplied with direct current are changed over to a.c. supply and extended as such. With reference to the use of boosters, as the feeders in question supply a network at a comparatively short distance from the existing manually operated stations, the pressure at the feeding point would have been excessive, also extra converting plant and boosters would have had to be installed at the manually operated stations. The relative advantages of motor-generators or mercury-arc rectifiers, as against rotary converters, are rather outside the scope of the paper, but it must be borne in mind that a rectifier has a drooping characteristic, the voltage dropping considerably as the load increases, viz. 6·4 per cent from 25 kW to 300 kW, which is unsatisfactory; also, as the vacuum pump has either to be kept running continuously or operated by remote control, the station is obviously not fully automatic.

Referring to Mr. Forrest's remarks, the converter is reactance-controlled, and no difficulty has been experienced with the power factor, which is as follows:—

200 amperes	unity
400 ,, ...	0·998 leading
600 ,, ...	0·995 ,,
800 ,, ...	0·995 ,,

This is certainly higher than we should get from an ordinary induction motor. The transformer is provided with tappings on the high-tension side. For lighting or traction pressures these tappings are controlled by a throw-over switch, which is interlocked with

the high-tension oil switch, any attempt to alter the position on load resulting in the latter switch being opened first.

In reply to Mr. Rogers, fuses are reduced to a minimum, and only the main fuses in the operating transformer circuit are in series with any of the operating relays. There is no battery as stand-by but the manually operated stations would act as stand-by in the case put forward. As regards the relative cost of a rotary converter with automatic switchgear and a mercury-arc rectifier with automatic switchgear, it is not clear on what amount of plant the figures given are based, as obviously both stations must be of the same capacity and provided with the same facilities; also the maintenance of one will greatly exceed that of the other, especially when the rectifier is of the glass-bulb pattern. The converter does its own balancing, whereas in a rectifier either a balancer or battery must be used, or else low-tension rectifiers in series, the latter, of course, being very inefficient.

In reply to Mr. Rogers's queries: (1) One visit a week is quite sufficient for inspection purposes, though more attention is being paid at present, until the inspectors are thoroughly conversant with the plant. (2) The average daily machine load factor, over 24 hours, is about 30 per cent. (3) The station cannot be started other than by the automatic gear, but in the event of any particular piece of apparatus failing this can be cut out and the station will still function automatically. (4) The "lock-out" relay is provided with special contacts for indicating externally that it has operated. These can be coupled to a red lamp outside the station, and instructions given to the police to notify the Electricity Department, or the contacts can be coupled to the private telephone wires, and give indication to the telephone operator. It has not been found necessary to adopt either of the above, as it is clear that the manually operated stations will be aware, owing to their increased load, that there is trouble. (5) The station is equipped with a recording ammeter and voltmeter, which are also an indication of the times of operating.

Mr. Groves mentions the use of boosters; this has been dealt with elsewhere. Cable losses were purposely ignored, as the case for the substation as against new feeders was strong enough without taking them into account.

Dr. Garrard refers to the use of economy resistances. These are only used on the main contactors (12) and (16) and the feeder contactors (40) and (41), which are across the d.c. bars; in no case are economy resistances used on the a.c. contactors. £1 795 represents the extra cost for a 500 kW converter and this amount would, of course, be reduced considerably with a reduced output, as obviously all main contactors, grid resistances, busbars, etc., would be smaller in comparison. The question of the relative merits of tap-starting as against other methods of starting, and also the starting-up of a second converter if installed at a later date, have been dealt with elsewhere in the reply. The grid resistance is provided as a safeguard to the station plant, the feeder protection taking care of a faulty feeder. If the manually operated stations failed, the load would become too heavy for the automatic station plant to deal with, and the grid resistance would cut in to limit the output. As it takes about 8 minutes for the grids to arrive at the requisite temperature to shut the plant down, the manually operated stations have a margin of time to get going again. The actual time required to put the converter on load is 41 seconds if the polarity is correct, and 45 seconds if the polarity has to be corrected.

In reply to Mr. Cooper, so far there have been no faults on any of the relays, nor does there appear to be any reason why they should occur. The relays are all of sound construction and very robust. Regarding the suggestion to fit a relay on the vacuum pump of a mercury arc rectifier, unfortunately this is a difficult matter which has not yet been overcome; it is, however, receiving very considerable attention.

SOME PROBLEMS IN HIGH-SPEED ALTERNATORS, AND THEIR SOLUTION.

By J. ROSEN, Member.

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SUMMARY.

It is the author's purpose to present concisely some of the more interesting problems encountered, and the methods adopted to solve them. The problems, although encountered in high-speed alternators, will be found to be of interest to engineers engaged in other branches of the electrical engineering industry.

The following subjects are considered:—

(1) The history and failures of turbo-alternators.
(2) Mechanical construction of rotors and caps supporting the coil ends.
(3) Stator windings and insulation.
(4) Stator slots.
(5) Alternator ventilation, water cooling and the necessity for clean air supply.
(6) Exciter instability.
(7) Eddy currents in rotors.
(8) Oscillograph tests, in explanation of exciter instability, showing the necessity for precautions when breaking the main field by means of a quick-break switch without any discharge resistance.

(1) THE HISTORY AND FAILURES OF TURBO-ALTERNATORS.

During the past ten years the development of large alternators running at high speeds has greatly advanced, and has brought out many interesting problems of design, construction, and operation.

Since the first steam-turbine-driven dynamo* (10 e.h.p., 100 volts, 75 amperes, running at 18 000 r.p.m.) was designed and constructed in 1884 by Sir Charles Parsons, engineers have recognized that high speeds of rotation are essential to direct-coupled, steam-turbine-driven machinery.

The velocity attained by a fluid when forced out of an orifice in the form of a jet is inversely proportional to the square root of the density, so that low density of working fluid implies high velocity of efflux from a nozzle. Also, theory and experiment prove that, to obtain good efficiency, the peripheral speed in a turbine must be comparable with the jet speed; so that, in turbines driven by steam, which has comparatively low density (only 1/140 of that of water at high pressure and 1/40 000 at 29 in. vacuum), the peripheral speed must be sufficiently high to obtain good steam economy. In practice, this means high speeds of rotation for the turbine and for the alternator, where the latter is direct coupled to the turbine shaft.†

The frequency for most electrification schemes in this country, however, is 50 periods per second, which limits the alternator speed to 3 000 r.p.m.

* British Patent, Nos. 6734/1884 and 14723/1884.
† The term "high speeds" is used in a relative sense, i.e. in comparison with reciprocating-piston engine practice.

Whilst this speed has been found suitable for moderate outputs, it is not sufficiently high to enable the best economy to be realized in small commercial turbines of 1 000 kW and below, a circumstance which

TABLE 1.

Parsons Alternators.

Year of installation	Output	Power factor	Speed
	kVA		r.p.m.
1909	1 250	0·8	3 000
1910	1 875	0·8	3 000
1913	2 060	0·8	3 000
1914	2 500	0·8	3 000
1917	3 750	0·8	3 000
1918	6 475	0·85	3 000
1919	7 500	0·8	3 000
1921	10 000	0·8	3 000
1922	12 500	0·8	3 000
1922	15 600	0·8	3 000
1922	18 750	0·8	3 000
Under construction	25 000	0·8	3 000
1911	2 140	0·7	2 000
1911	2 500	0·8	2 400
1911	3 200	0·75	2 400
1915	3 750	0·8	2 400
1916	14 700	0·75	2 400
1921	17 650	0·85	2 400
1909	2 860	0·7	1 500
1910	8 575	0·7	1 000
1913	13 150	0·95	1 500
1913	25 000	1·0	750
1915	19 000	0·95	1 000
1918	14 750	0·95	1 500
1920	18 750	0·8	1 500
1922	25 000	0·8	1 500
Under construction	47 500	0·8	1 800

has led to the development of geared turbo-alternators for these outputs.

About 1887, de Laval had developed a satisfactory form of double helical reduction gearing for use with his simple impulse turbine, and showed that single-reduction gears with a ratio of 10 to 1 could be successfully constructed for transmitting small powers.

About 1912, however, Sir Charles Parsons further developed this form of gearing for coupling to electrical machinery turbines of much greater output; and, by

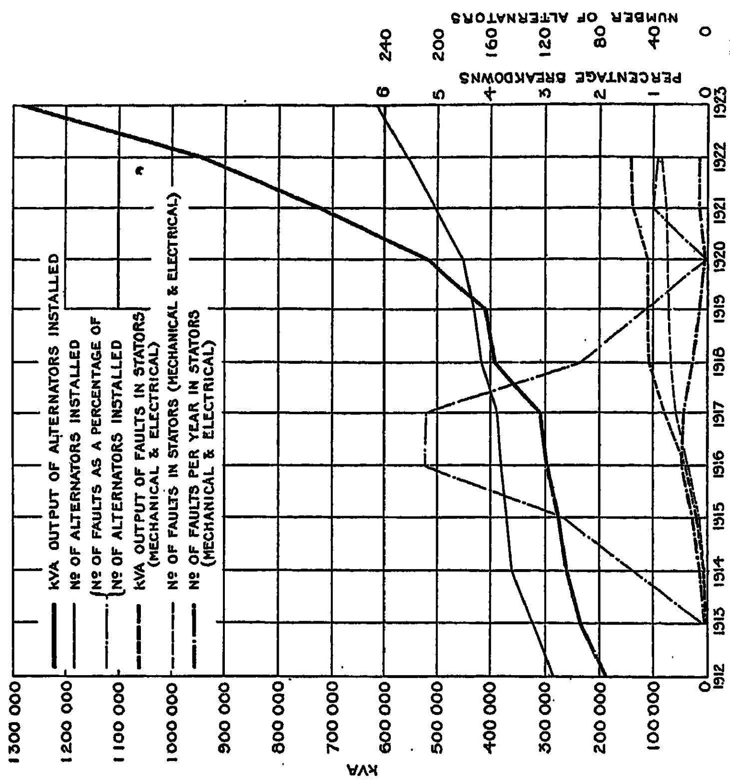


FIG. 2.—Output and number of Parsons turbo-alternators in commission.

FIG. 3.—Sand-blast action on conductors.

(This was shown as a lantern slide.)

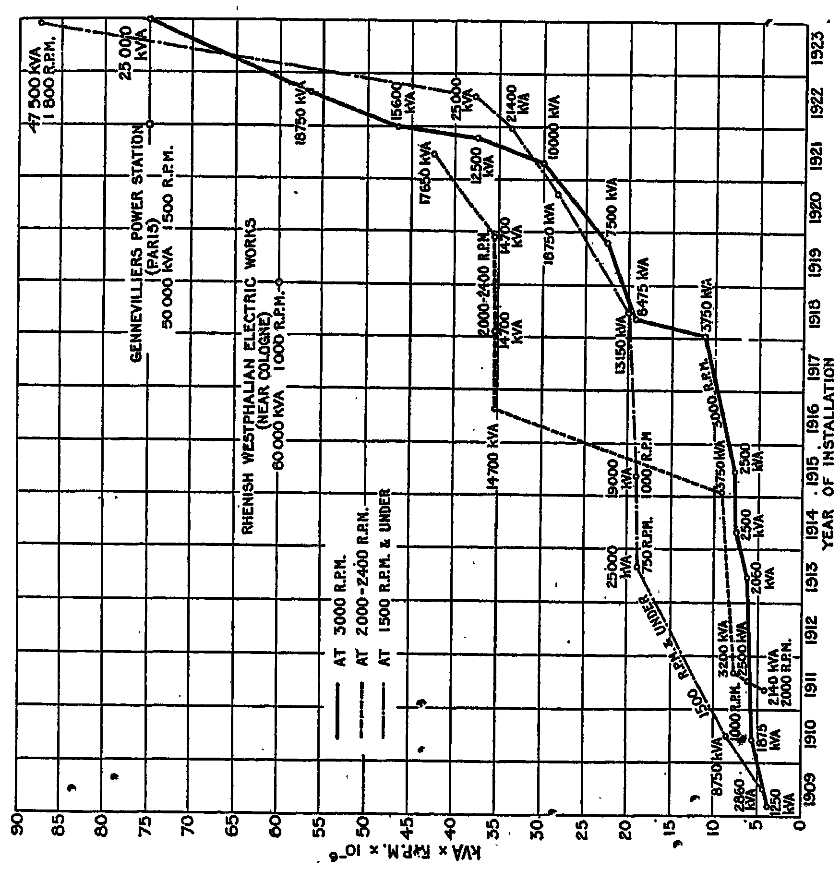


FIG. 1.—kVA × r.p.m. of the largest Parsons alternators manufactured each year.

the use of modern single-reduction gears, a turbine can be run up to some 5 000–6 000 r.p.m.: the speed of the alternator, now being optional, is made low (500–750 r.p.m.), so that ordinary materials and low-speed construction may be adopted, with a view to reduced cost.

With regard to large units, it is only within the last few years that alternators of very large output at high speeds of rotation have been built.

Table 1 gives the sizes of the largest Parsons alternators, of different speeds, manufactured each year, and demonstrates, on the whole, a gradual increase in capacity of individual machines. The curves in Fig. 1 perhaps illustrate this more clearly. During the period of the late war, the size of plant at 3 000 r.p.m. remained comparatively steady. The curves are of great interest, as it will be seen that the 14 700-kVA alternators, again referred to later in the paper, were a great advance upon machines running at the time. From the data obtained from the five 14 700-kVA alternators, experience was gained which enabled Messrs. Parsons to design and manufacture alternators of even greater outputs at 3 000 r.p.m., without exceeding the electrical and mechanical limits which had been proved satisfactory after several years' trial. Credit is also due to the Newcastle-upon-Tyne Electric Supply Company, and their consulting engineers, Messrs. Merz and McLellan, for their courage and initiative in installing a pioneer plant which was such a notable advance on any existing practice.

In 1915, 3 750 kVA was considered to be a large output at 3 000 r.p.m., whereas, to-day, alternators of 20 000 kVA continuous maximum rating have been manufactured in this country. In America at present, 9 375 kVA continuous maximum rating is the largest output at 3 600 r.p.m. From the author's discussions with engineers and designers in America, he found that the difficulty in designing at the higher speeds lay in the alternator and not in the turbine, and that ventilation appeared to be a limiting factor.

With the improved materials and methods of ventilation, combined with more accurate proportioning, large alternators at high speeds are certainly no less reliable than the earlier and smaller machines. The accompanying curves, Fig. 2, indicate all the breakdowns of Parsons alternator stators in the British Isles during the past ten years. The total output and the number

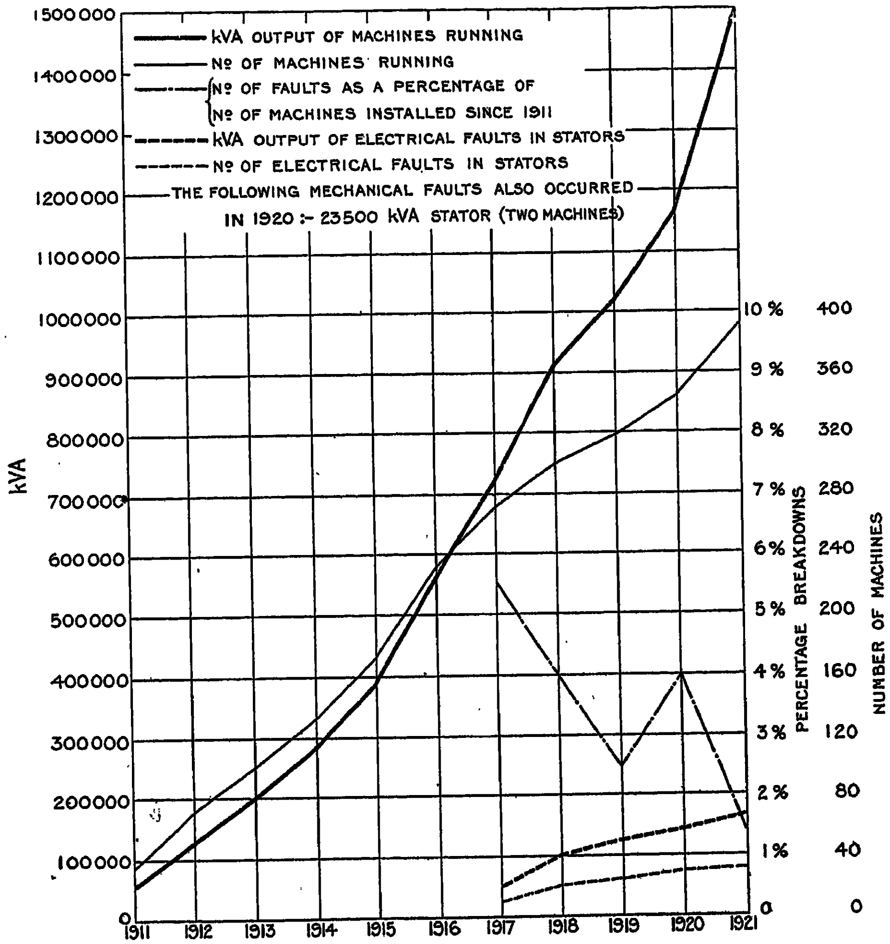


FIG. 4.—Number and output of Metropolitan-Vickers turbo-alternators in service.

of machines installed during this period are also given.

During the period 1916–1917 there were several failures, due to reasons which are now clear, the faults being at the alternator terminals and on the end windings, due to overheating, insufficient supports against sudden short-circuits, and to station conditions such as moisture in air ducts. The two breakdowns for 1922 (Fig. 2) were of alternators built 20 years ago. One involved a minor repair, and the second machine had to be rewound. Only the failures of stators are included, as the failures of rotors of which the author has experience have been few during this period, and the difficulties have been mechanical and readily overcome. This record speaks for itself, especially when it is remembered that during a large portion of this period the plants were run at maximum output night and day, owing to war conditions. Although the number of machines in commission has increased, the number of breakdowns has diminished. The improvement is still more striking when it is considered that the conditions of operation in a modern power station have become more severe with the advance of time.

To achieve these results, advantage has been taken of every opportunity of incorporating later improvements into alternators already in operation. The results would have been even better had it not been that, because of the circumstances previously mentioned, it was not possible to shut down some of the plants even for a short time in order to make the necessary improvements.

In one plant some of the stator conductor insulating-tubes were found to be eroded. The ground near to the air-duct entrance to the alternator foundations was being excavated, and fine grit and dust were drawn into the alternator air-duct and air-gap, being thrown out by the rotor at a velocity corresponding approximately to its peripheral speed, causing a sand-blast action, which was sufficient to cut into the portions of the insulating tubes exposed between the core sections. The remainder of the tubes were protected by the core, as the slot was of the tunnel formation. A photograph of two of the conductor tubes is shown in Fig. 3. It is of interest to record that, although at least seven conductor bars were damaged, being bared to the copper, the alternator did not break down. Protection is now provided by means of teak-wood packing at the top of the slots, driven in along the whole length of the core.

The fault mentioned above was found during the annual overhaul, and emphasizes the advisability for periodic examination and testing in order to avoid mishaps which are beyond the control of both power station engineers and manufacturers.

Fig. 4 gives the curves for machines of the Metropolitan-Vickers Electrical Company's manufacture, which also show a downward tendency in the percentage of breakdowns.*

(2) Mechanical Construction of Rotor.

The principal mechanical problems are encountered in the construction of the rotor. Improved methods of manufacture, and more systematic inspection and testing, have eliminated troubles due to flaws in the material.

The barrel formation of rotor, in which the exciting windings are embedded in radial slots formed between the poles, has proved itself eminently suitable for high-speed design. The details of the rotor construction depend upon experience, and upon the design of the remaining parts of the alternator.

When the first 14 700-kVA alternators running at 2 400 r.p.m. were under consideration in 1914, the problem of the best construction of rotor was thoroughly thrashed out. The merits of the plate rotor with a through shaft, of the plate rotor with bolted-on shaft ends, of the rotor built with thin laminations on a through shaft, and of the single-forging rotor, were given careful consideration by Sir Charles Parsons and the author. The simple solid forging was finally chosen, and experience has shown that it is the most suitable construction.

After careful consideration of the peripheral speeds of machines already running, it was decided to adopt the very conservative and safe figure of 300 ft. per second, at which peripheral speed several Parsons alternators had been running for many years at speeds from 1 000 to 3 000 r.p.m. Obviously this meant a long rotor body, and its length was actually 105 in., with a diameter of 29 in., giving a ratio of pole length to pole diameter of 3·62; this ratio was more than double that of any large alternator, either running or under construction, at that time. From careful calculations and comparison with these earlier machines it was decided that there might be a critical speed at 1 600 r.p.m. (On running the rotor of the first of these machines later, it was found to vibrate slightly between 1 200 r.p.m. and 1 600 r.p.m., but after the final balancing no undue vibration could be detected at or below 3 000 r.p.m., i.e. 25 per cent above the normal speed.)

It is of interest to note here that, in a paper read before this Institution in 1908, the pioneer Parsons direct-current armature was described,* having a core diameter of $2\frac{1}{4}$ in. and a core length of 8 in., giving a ratio of core length to core diameter of $3\frac{5}{9}$. This armature ran at 18 000 r.p.m. and had a through shaft. Most of the earlier rotors and armatures successfully ran through two or more critical speeds before reaching the running speed.

In addition to other novel features, the rotors of the 14 700-kVA alternators were water-cooled, and details are given in Section (5). It was realized that there might be difficulty in dissipating heat from such a long rotor by the usual methods of air ventilation, so that water-cooling was introduced to give confidence upon this question, leaving the designers a free hand to deal with the mechanical problems.

Rotor caps.—The caps for supporting the rotor end windings are one of the limiting factors in any design, and it is here that the advantages of comparatively low peripheral speeds become apparent. The material now obtainable for the caps has an ultimate strength of 65 tons per sq. in., with a yield point of not less than 48 tons per sq. in. The material is also ductile, as

* *Journal I.E.E.*, 1921, vol. 59, p. 299.

* *Journal I.E.E.*, 1908, vol. 41, p. 286.

shown by the elongation on a test piece 0·564 in. diameter (area = 0·25 sq. in.), of 15 per cent on 2 in., with a reduction of area of 50 per cent.

With the comparatively low peripheral speed the stress in the caps is kept below 12 tons per sq. in. at the normal speed; in the 14 700-kVA alternators before mentioned the mean hoop stress in the caps was less than 9 tons per sq. in.

The rotor end windings are not evenly distributed under the caps, a circumstance that leads to a drawback, which is more apparent in the 2-pole rotors, namely that the caps, not being uniformly stressed, tend to become oval in service. Moreover, it is possible to deform a cap 25 in. diameter, 1 in. thick, by as much as $\frac{1}{8}$ in. on the diameter during its assembly over the windings. This phenomenon, when first observed, gave much food for thought, and it was considered desirable

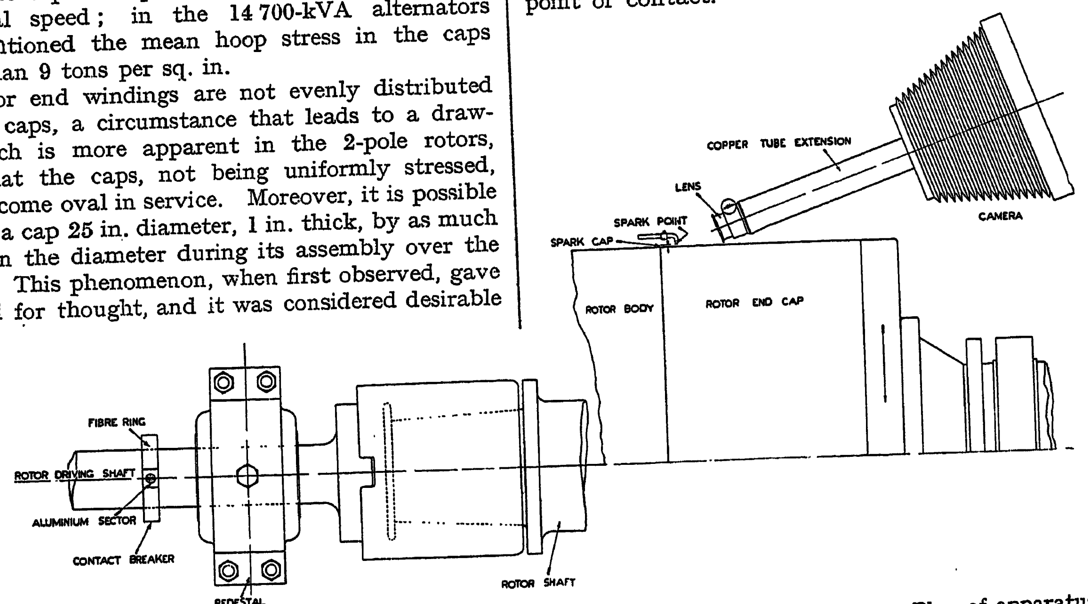


FIG. 5.—Experiment on rotor end cap, to determine the distortion when running at 3 000 r.p.m. Plan of apparatus for photographing spark.

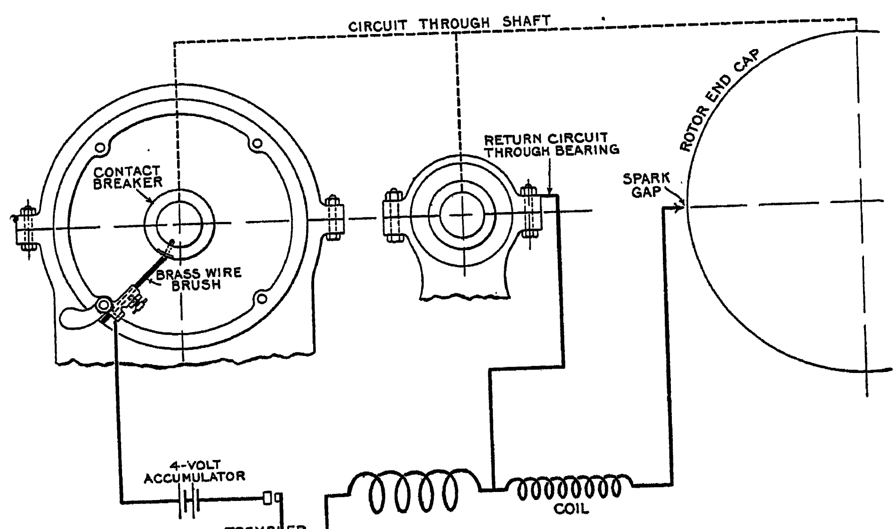


FIG. 6.—Diagram of connections for experiment on rotor end cap.

to obtain exact information as to the actual deformation of the caps with the completed rotor running at full speed. The investigations were carried out early last year (1921) and a rotor from a 15 000-kVA alternator running at 3 000 r.p.m. was selected for the experiments.

The rotor was adjusted in a special machine used for the dynamic balancing of alternator rotors, and was driven by a 600-b.h.p. low-speed motor, stepping up through a 6/1 gearing and flexible coupling, thus eliminating any side pull such as that due to a belt. The oil clearance between the rotor journals and bearings was a minimum.

The eccentricity of the cap was obtained by measuring the varying clearances between the cap and a fixed point or contact.

Two methods of obtaining the eccentricity were originally proposed:

(1) Using a microphone to record the loudness of the note in a telephone receiver, or to give a record on an oscillograph.
(2) Photographing the length of an electric spark jumping across the gap between a fixed contact and the cap.

The microphone method is inadmissible unless the cap is of magnetic material, and there is obvious difficulty in obtaining accurately, by this method, the shape of the cap while running; the second method was therefore adopted.

The maximum extension of the cap occurred adjacent to the rotor body. The extension on the diameter was 0·01 in. between poles, and 0·025 in. at the centre of the poles. The cap was therefore only slightly distorted. The results agreed very closely with calculation.

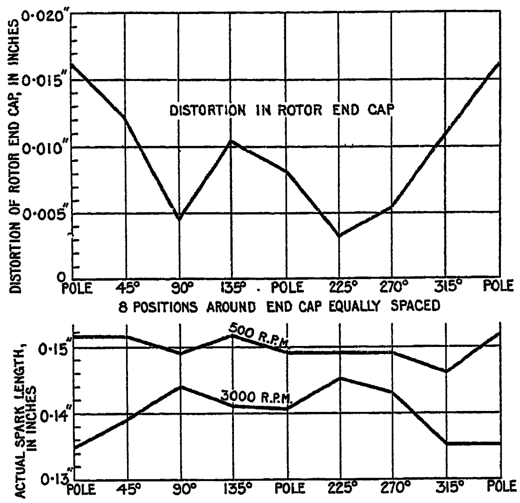


FIG. 7.—Graphs showing distortion in rotor end cap.

TABLE OF READINGS AND CALCULATIONS FROM EXPERIMENT.

SPARK GAP = 0·15 IN.

(1) Position on rotor	(2) Length of spark at 3 000 r.p.m. on film	(3) Length of spark at 500 r.p.m. on film	(4) Difference (3) − (2)	(5) Actual distort on (4) × $\frac{0{\cdot}15}{1{\cdot}10}$
pole	0·99	1·11	0·12	0·0163
45°	1·02	1·11	0·09	0·0122
90°	1·055	1·09	0·035	0·00475
135°	1·035	1·11	0·075	0·0104
pole	1·03	1·09	0·06	0·00815
225°	1·065	1·09	0·025	0·0034
270°	1·05	1·09	0·04	0·0054
315°	0·99	1·07	0·08	0·0109
pole	0·99	1·11	0·12	0·0163

It will perhaps be of interest to give here a very short description of the experiment. The sparking contact, Figs. 5 and 6, was supported from the heavy baseplate and made adjustable axially along the cap. The brush of the contact breaker, which it was found more convenient to fit to the driving motor shaft, could be moved round to make the spark at any desired circumferential position on the cap. Fig. 7 gives in graphical and tabular form the results of one set of readings taken at 500 r.p.m. and 3 000 r.p.m. The procedure in calculation is given at the head of the table following Fig. 7.

At the former speed it was assumed that there was no appreciable distortion of the cap—the difference in the readings will therefore give the distortion due to the rotation at 3 000 r.p.m. The illustrations are diagrammatic, but some idea of the difficulties in running, and due to windage, may be gauged from them, when it is remembered that the maximum peripheral speed of the rotor, which weighed 15 tons, was nearly 400 ft. per second.

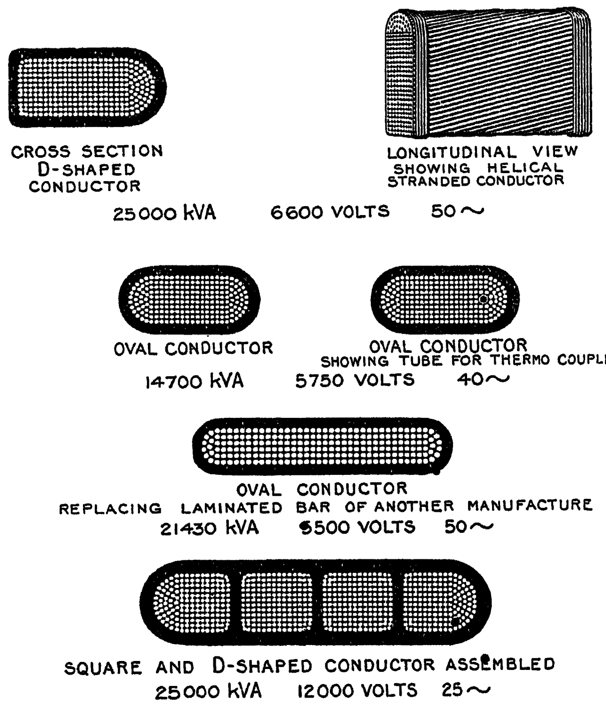


FIG. 8.—Sections of insulated conductors made from Parsons helically stranded coreless cable, without crushing.

FIGS. 9 and 10.—Special cable-making machine.
(These were shown as lantern slides.)

(3) STATOR WINDINGS AND INSULATION.

Early alternator stators were hand wound, with a continuous length of cable of the same cross-section throughout. The insulating tubes in the slots were moulded separately, usually of tape and fibrous material such as press-spahn or leatheroid. They were placed in position in the slots, and the cable was wound or pulled through them. The cable was insulated by hand during the process of winding. This construction, although of proved reliability, was laborious and expensive, and became more difficult with the increasing size of alternators. The winding space was not used effectively; the output was limited and the cost unduly high.

To overcome these difficulties, the conductors in the core are now made separate from the end connectors. The former are made by Messrs. C. A. Parsons & Co., of their stranded coreless cable,* shown in Fig. 8, in

* British Patent, Nos. 16 620/08 and 184 574.

which the individual strands are insulated and spiralled in a definite lay, to eliminate eddy-current losses in the cable. The end connectors are made of copper straps, which form a good mechanical construction for bracing against the forces set up in the winding at the moment of sudden short-circuits.

The cable employed is constructed on a special cable-making machine,* and is built up of copper strands separately insulated; it can be manufactured in any desired shape without a central core and without crushing. There is therefore no necessity to deform the cable after it leaves the cable-making machine. By this means the danger of short-circuits developing between individual strands is eliminated. Some examples are given in Figs. 9 and 10, illustrating the accurate forming of the cable, which leaves the machine in its final form without crushing.

There appears to be some misunderstanding in the minds of engineers as to the properties of the Parsons stranded cable. In the early days, when armatures were wound with round stranded cable, there was no difficulty in obtaining a good construction. However, later, with oval cables, cable makers would only supply round cable crushed to the desired shape, or a cable with a paper core. The former was undesirable, as the insulation on the individual strands of the conductor was broken in the process of crushing. As a result, excessive heating occurred due to the induced eddy currents. The paper-core cable had the obvious disadvantage of a low space factor, with the result that it was impossible to design an economical machine, and limits were placed on the output. This type of cable was also very difficult to handle and to bend into suitable shape for winding. The Parsons patented cable overcomes these difficulties, and to-day is gradually obtaining recognition, so that it is being used in the construction of transformers and alternators by other manufacturing firms in this country and on the Continent; in America its use is now under consideration. Later still, multiple joints * were adopted for connecting the cables forming the core conductors to the end connectors. This improvement is successful in minimizing the loss due to eddy currents induced in the joints. An example of a conductor with three separate joints at each end is given in Fig. 11.

With the improved winding construction, mica became, and still remains, the principal component in the material of the insulating tubes. Instead of the tube being formed and the conductors wound separately, the slot insulation is moulded round the conductors, forming one bar ready for placing into the slot. The insulation is applied by the Parsons Company by a special machine, the design of which is based on the principle of the familiar hand cigarette-making machine. The insulation passes over a hot table and is carried round by a taut canvas band, being thus tightly wrapped round the stator conductor bar. The machine in question is sufficiently flexible to be able to insulate a small bar weighing a few pounds, up to bars weighing 3 cwts. The end connectors are also insulated separately before assembly in the stator; after assembly, it is only necessary to insulate the joints connecting the end windings with the slot conductors. With these new methods employed in winding, it has become possible to use improved insulating materials, and to supervise more strictly this important part of the work.

In earlier practice, methods of manufacture had been developed in which the insulation moulded round the conductors formed a compact mass with the copper, and had almost a metallic ring, when knocked with a hammer; conductors insulated in this way made a great appeal to engineers, owing to their resemblance to a

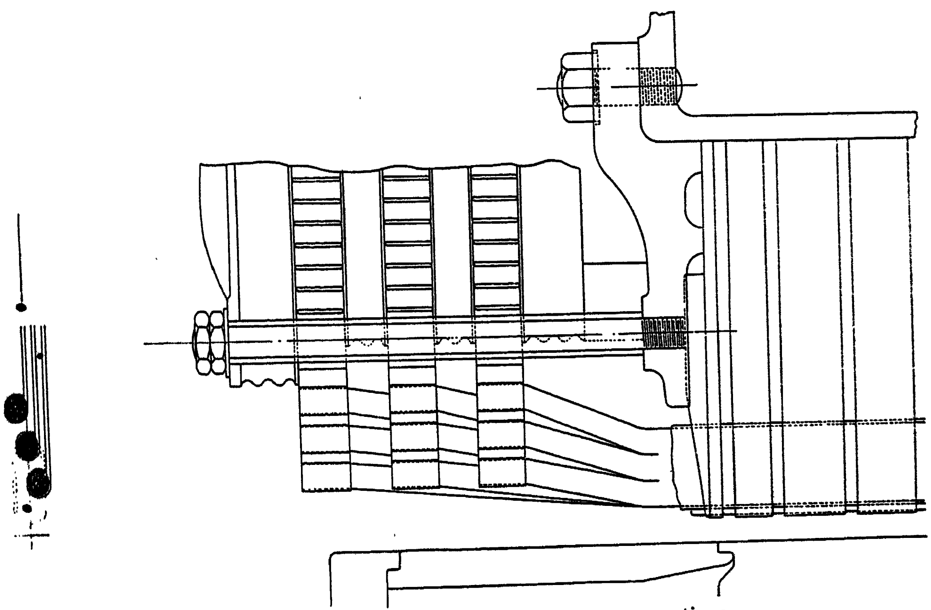


FIG. 11.—Multiple joints for stator end connections.

* British Patent, No. 16 620/08.

* British Patent, No. 126 124.

metallic structure. The disadvantages of this method of insulation did not appear until later.

During 1913, on drying out the stator windings of a 2 500-kVA, 6 600-volt alternator, cracks developed in the hard insulating tubes, which broke down to earth under the high-pressure insulation test. The reason for this failure was not appreciated until a similar fault developed on another stator, and the whole position was investigated. The explanation is a simple one. When the alternator gets hot, the conductors and insulating tubes expand and lengthen. The copper conductor, having the higher coefficient of expansion, lengthens more than the tube and, as both form a solid mass, one has to give way. It is always the tube. This illustration shows clearly how a modification, although apparently an improvement, may have disadvantages which only develop on trial under operating conditions. It shows also the necessity for caution in departing from proved methods of construction.

Yet, on looking into other spheres of electrical work, it is not unreasonable to reflect that the difficulties might have been foreseen. Take one example—an ordinary electric glow lamp. The metal "leads" to the filament must have the same coefficient of expansion as that of the glass through which they pass, otherwise, when the lamp is switched on, and becomes heated, the glass and wires expand unequally and the glass cracks.

To remove the expansion difficulty, and to retain the insulating tube moulded directly on to the conductors, it is necessary to use an insulation having the same coefficient of expansion as that of copper, or, alternatively, to make the insulation sufficiently flexible to take up the difference in expansion. The former solution is not yet obtainable. A flexible mica insulation had therefore to be devised. This insulation, after a great deal of investigation, was finally obtained and, when the spirit has been evaporated from the varnish binding the mica flakes together, the remaining oils ensure that the insulation retains sufficiently elastic properties at the operating temperatures of the alternator. It must be remembered that the sides of the conductor slots also grip the insulating tube; just as between the copper conductor and the tube there is relative movement, so is there also between the tube and the iron core. Flexible insulation has provided a satisfactory solution of both difficulties.

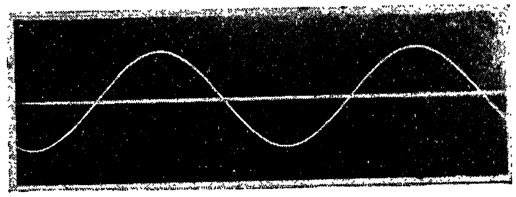
As an alternative, if a hard moulded insulation is used, the following precautions should be taken. A thin layer of flexible insulation should be applied between the conductor and the hard tube, and also outside the latter. This outer layer of elastic material might be applied to the sides of the slots so as to present a smooth surface to the insulating tube. A suitable bituminous compound, becoming elastic at the operating temperatures, would serve the purpose.

It must be borne in mind that whatever insulation is employed must not be brittle. If brittle insulation is used, cracks will also develop when the windings are subject to the forces occurring on short-circuits. The insulation must not pulverize. Too much stress cannot be laid upon these qualities.

Experience has proved that movement of the end windings as a whole cannot entirely be prevented. On one occasion a dead short-circuit occurred across the terminals of one of the largest alternators while on full load. Careful examination showed that, owing to the shrinkage of insulation and packings relieving the pressure of the clamps, the stator end windings in one place had moved $\frac{1}{2}$ in., but had afterwards sprung back to their normal position.

(4) Stator Slots.

In the author's opinion, the tunnel formation of slot for receiving the stator conductor bars has many advantages over the open slot formation. The construction may be a little more expensive to manufacture, but, when correctly designed, the windings are more accessible for examination and withdrawal, if necessary, than former-wound coils in completely open slots. This advantage is more noticeable in turbo-alternators, as the number of poles rarely exceeds two or four, giving a long winding-pitch. The advantages are also still more apparent in the largest turbo-alternators, since the number of conductors per slot is small.


(a)

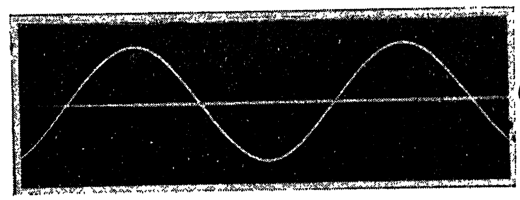

(b)

Fig. 12.—Oscillograph curves for 18 750-kVA 6 500-V alternator on open circuit.
(a) Between phases. (b) Between phase and earth.

The slot is punched with a full radius top and bottom, giving a sound mechanical construction of core, and the insulating tube, of the oval cross-section required to fill the slot, is readily moulded around the conductor bar.

With the tunnel slot construction the flux pulsations are minimized, and, as the stator bore has an uninterrupted contour, the circulating currents induced in the rotor body are reduced to a minimum and the efficiency of the alternator is improved. In the closed slot construction the leakage of flux across the iron bridge enables a high inherent reactance to be obtained without resorting to abnormal proportions of the slot.

Again, by the use of the tunnel slot it is possible to obtain an alternator voltage wave-form entirely free from ripples. With the open type of slot it is difficult to remove the ripple at the peak of the voltage wave-form. Fig. 12 gives the oscillograms of the open-circuit voltage of a Parsons 18 750-kVA alternator with tunnel

slots. Fig. 13 gives the oscillograms with a load of 8 000 kVA and a power factor of 0·95. Both sets of oscillograms give the voltage between phase terminals, and between the phase terminal and the star point. There are no pronounced harmonics, and on load the maximum deviation from a sine wave of the pressure between the line terminal and earth is 2·1 per cent. This improvement in wave-form is most desirable, especially where the supply of power is given through transformers or through converting apparatus such as rotary converters. It avoids disturbance in telephone operation and difficulties with parallel running, since it eliminates circulating currents, and it gives the supply engineer opportunities to earth without anticipating trouble.

If tooth ripples are present in the voltage wave-form, there is the danger of resonance in the distribution system causing breakdowns of the cable insulation. Such a series of failures was recently brought to the

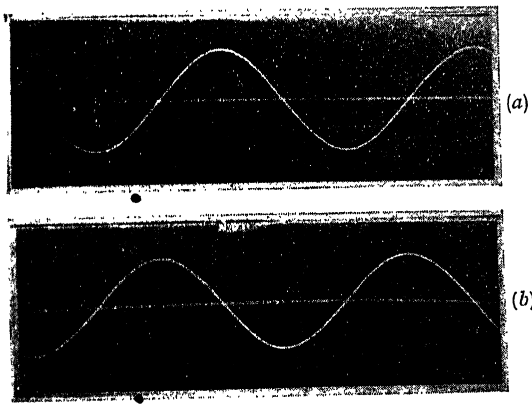


FIG. 13.—Oscillograph curves for 18 750-kVA 6 500-V alternator on load of 8 000 kVA at 0·95 power factor.
(a) Between phases. (b) Between phase and earth.

FIG. 14.—Stator tooth supports of different dates.

FIG. 15.—The effect of the vibration of spacers and core plates in a particular case.

(Figs. 14 and 15 were shown as lantern slides.)

author's notice; they were finally ascribed to the above cause, and were overcome by connecting in circuit another feeder to alter the impedance of the external circuit.

Some years ago, two power stations about one mile apart were running in parallel, and it was found that the electrical instruments in one station were indicating more load than the alternators could possibly give, whereas the recorded output at the second station was too low. This error in the reading of the instrument was finally traced to the high-frequency circulating currents through the alternator star-points, which were earthed in both stations.

Stator tooth supports.—The supports to the teeth between the slots have in the past been a source of difficulty. Views of the supports used at different dates are given in Fig. 14. The H-section spacer shown at A has proved to be the most suitable support. The U-shaped spacer shown at B gave trouble due to insufficient bearing surface. In one alternator the vibration of the spacers and core plates was sufficient to taper away the spacer to less than half its original height, and to cut through the adjacent thick plates supporting the core, as illustrated in Fig. 15. Some of the spacers broke away at the shoulder and were pulled on to the periphery of the rotor. At the time the fault was found, it was impossible to shut the machine down and provide a remedy, as there was no other plant available to take the load.

(5) VENTILATION.

With the larger sizes and longer lengths of alternators (necessitated by comparatively low peripheral speeds) it becomes more difficult to ensure uniform cooling. In the usually accepted schemes of ventilation, air is drawn or forced in from the ends of the alternator only. The available area for the passage of air is limited, and the air is heated before getting to the centre of the alternator, which is consequently the hottest part. Such local high temperatures limit the output.

To obtain a scheme of ventilation in which the alternator shall be cooled uniformly throughout its entire length should be the aim of all designers, and it is necessary that the construction should be simple and easy to manufacture. Such a method is described in British Patent No. 15 585/1914, and, so far as the author is aware, the practical application of this scheme of ventilation is unique. The alternator, for ventilation purposes, is divided into separate air circuits in parallel, each with low resistance to the passage of the air. By this subdivision the alternator can be designed to have any desired length, and still be uniformly cooled. Fans attached to the rotor, or separately-driven fans, can be used. From Fig. 16 it will be seen that the air is forced into the separate pressure belts or compartments A, which are cast into the stator casing, alternating with the exhaust compartments B throughout the length of the alternator. From each pressure compartment the air passes through radial ducts into the body of the core. A portion of the air then passes between the stator teeth K round the conductors into the air-gap, where it divides and passes axially in both directions, and back radially into the adjacent compartments B. Only a portion of the air passes between the stator teeth K, the remainder being short-circuited through axial holes M, formed in the core immediately behind the conductor slots; this air joins the stream passing from the air-gap back into the exhaust compartments. The quantities of air short-circuited behind the conductors and passing through the air-gap are so proportioned as to obtain uniform cooling of all parts of the stator and rotor.

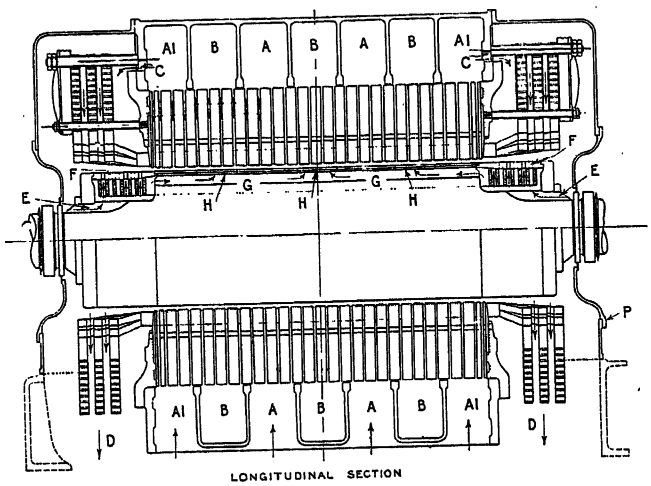
The stator end windings are ventilated from the end pressure compartments A1, from which the air is forced through suitably designed holes C in the end walls of the casing on to the end windings. Baffles are provided to direct the air round these windings before leaving at the outlet D in the end-winding protective shields P. These baffles (Fig. 17) are so designed and arranged that the cool air impinges on each section of the end windings, eliminating hot spots.

The rotor is mainly surface cooled, but, in addition, air is also drawn in under the balancing discs E. A portion of this air is forced through the holes F in the rotor end caps, and the remainder is drawn into the axial slots G machined along the rotor poles. Gaps H are left between the keys in these ventilating slots, so that air is thrown out opposite the exhaust compartments in the stator casing.

With the scheme of ventilation described, a separately-driven fan is recommended. It is impracticable to construct a highly efficient fan for fitting on the ends of the alternator rotor. When integral fans are used, sufficient air is passed only at the expense of unnecessary power and consequent loss of efficiency. It is also impracticable, without increasing the length of the plant unduly, to obtain a suitably designed vortex chamber in the end shields, owing to the restricted space available and to the baffling effect of the stator end windings. The author has had considerable experience of separate motor-driven fans on alternators of all sizes, and on none of these plants has a breakdown occurred on either fan or motor. It is needless to point out that it is essential to obtain a good design of fan and motor, and to see that the latter runs well within its maximum rating. The motor-driven fan can be designed with the maximum efficiency, and it has been proved that a consequent gain of as much as 1 per cent in the efficiency of the alternator is possible.

Air cleaning.—A large quantity of air is used to cool an alternator, and its weight may actually exceed that of the steam passing through the turbine per unit time; it is therefore essential that the air should be clean. A 10 000-kW turbine, with a steam consumption of 10·0 lb. per kilowatt-hour, passes 1 670 lb. of steam per minute, whereas the weight of the ventilating air passing through the alternator is 2 740 lb., i.e. 45 per cent more during the same period, assuming a flow of 36 000 cubic ft. per minute.

Until comparatively recently, it was the universal practice to ventilate the alternator by means of a continuous stream of fresh air forced through it, either by separately-driven fans or by fans integral with the alternator rotor. In this system the heated air may be either thrown away outside the engine room, or utilized in the boiler stokeholds for the combustion of the fuel. If efficient means of cleaning the air were not adopted, the passage of the very large quantities of fresh air necessary would quickly result in the silting



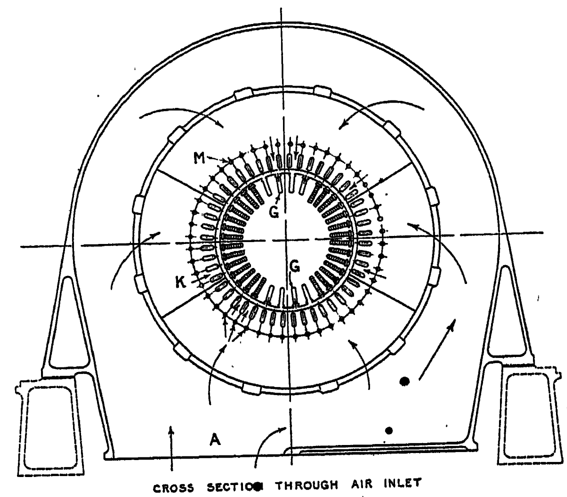


FIG. 16.—Parsons ventilation system of an alternator.

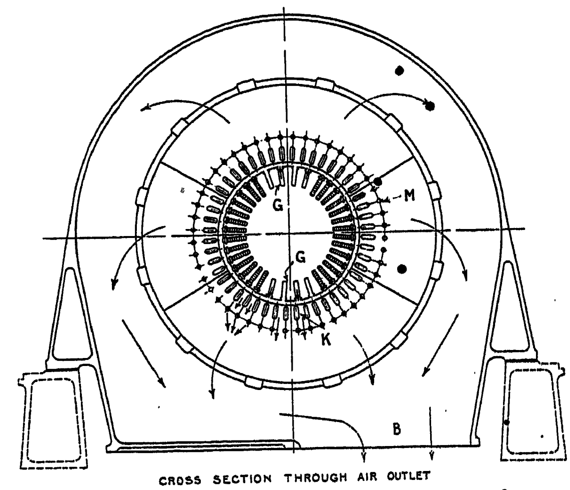


FIG. 17.—Design and arrangement of air baffles.

(This was shown as a lantern slide.)

up with dust of the ventilating ducts through the alternator windings and core.

In the early days the cleaning apparatus consisted of filter cloths, presenting a considerable surface to the passage of the air. The principal disadvantages of this apparatus are :—

(1) The large space occupied.
(2) The necessity for periodic removal of accumulated dust, some of which reaches the windings in spite of all precautions.
(3) The danger of fire, due to the inflammable nature of the filter cloth.
(4) The length of external ducts for conveying the air.

As a result of the first three disadvantages mentioned, the dry air-filter was generally superseded by the wet air-filter, in which the air was brought into intimate contact with water.

In this type of filter it is possible not only to clean the air, but also to lower the temperature of the air entering the machine below that of the surrounding atmosphere. The great disadvantage of the wet air-filter is that there is always a danger of free moisture being carried over into the alternator and collecting on the windings. This danger cannot be altogether eliminated even with long air ducts, large settling chambers, and fans between the filter and the alternator.

In 1913, few reliable data were available as to the conditions under which wet air-filters were operating. Messrs. C. A. Parsons and Co. decided to investigate thoroughly the whole position, and tests were carried out on a number of filters of various makes installed in different parts of the country. These tests showed that in a great many plants free moisture was present in the filtered air entering the alternator. In some machines the insulation resistance of the stator windings was reduced to a dangerous figure. The fault was not only in the filter, but also in the lay-out of the ducts between the filter and the alternator. The circulation of air through the filter was not uniform. As the danger due to free moisture was so great, a number of wet air-filters were put out of commission, and in other plants the water was periodically shut off from the filters so as to give the alternator insulation resistance time to rise.

A wet air-filter of a capacity of 25 000 cubic ft. of air per minute was installed at the Heaton works, and exhaustive tests were made on it. The results clearly indicated that the design of filter under test was wrong. A new type of wet air-filter resulted. Although more reliable wet air-filters are now available, great care must be taken in the lay-out of the filters in relation to the alternator, and precautions must be taken in their operation. The filters are sometimes put out of commission during frosty weather owing to the danger of the water freezing. Steam heaters have been used to overcome this difficulty.

It was felt, however, by Messrs. Parsons that the time had come to attempt to eliminate the difficulties due to the air coming into contact with water. It was suggested that some form of apparatus which cooled the air circulating round a closed system of ducts might be an improvement; the same air would be repeatedly circulated, and it would therefore not be necessary to clean, but only to cool it. In addition, it was decided that the air must not come into contact with the cooling fluid. Some years previously this same question had been discussed, but at that time it was considered inadvisable to proceed with such a cooler which, with the data then available, was found to be both cumbersome and expensive to manufacture.

Renewed tests were now started on a design of air cooler which was in fact a motor-car radiator in reverse operation, its function being to absorb heat from the air instead of to dissipate it. The cooler under test had copper tubes with sheet-iron gills, and was in reality a radiator taken from a 4-ton lorry. As a result of only a few experiments, it was found that such an air cooler was a commercial proposition. Elaborate experiments were carried out with an enclosed system of ducts, with the same air repeatedly circulated. An electric heater was used in the ducts for heating the air, the heat being subsequently extracted by the cooler.

Credit should be given to the staff of the Battersea Corporation Electricity Works who, in 1912, took out a patent for a cooler using water from the condensate, and proved the advantages of the enclosed air system. They installed their first cooler at Battersea power station, using plain tubes. The whole question was discussed with Messrs. Merz and McLellan, and an alternator air-cooler, to deal with 18 000 cubic ft. of air per minute, was installed in 1919 by Messrs. Parsons, on a 3 000-kW plant in the Blaydon power station of the Newcastle-upon-Tyne Electric Supply Co., to whom credit should also be given for placing an order for experimental plant for commercial use. This alternator air-cooler which, since its installation, has run without any fault developing, was the first design with gilled tubes to be installed and put into commercial operation in this country. The Parsons Company has a number of coolers for alternators, with a total capacity of a quarter of a million kVA, either in operation or under construction, for this country or abroad. At the time the above-mentioned cooler was installed, the General Electric Co. of America was apparently experimenting on the same lines, and some of their results were published.*

There are several advantages attached to the closed-circuit system of ventilation. It is generally possible for the cooler to be installed inside the alternator foundation block, the only external plant being the fan with its short connecting air ducts. The system is therefore very compact. Little or no dirt can collect in the alternator, since practically the same air is continuously circulated round the system. Owing to slight unavoidable air leakages (which have to be made up) it is true that the circulated air is very gradually replaced, but the ducts can be so arranged that the leakage occurs at one point only, the incoming air being previously cleaned and dried. In the author's experience, however, this complication has proved unnecessary.

Another advantage of the closed-circuit system

* *General Electric Review*, 1920, vol. 23, p. 99.

lies in the fact that it reduces the fire risk, as the actual weight of air available to feed an internal fire in the machine is small and the oxygen therein would be rapidly consumed. The weight of air in the system of a 10 000-kW alternator would be only 80 lb.

The designers of the Gennevilliers power station, Paris, where coolers are installed, have planned a system for increasing the nitrogen content in the air to such an extent that it will not support combustion. This, in the author's opinion, is an unnecessary procedure.

Fig. 18 illustrates a simple lay-out of the closed-circuit air system of ventilation. The air is forced from the outlet of the fan D, through the alternator, into the foundation block in which is embodied the cooler C. On leaving the cooler, an air conduit E leads the cool air back to the suction side of the fan D.

Usually the cast-iron water boxes of the air cooler are placed vertically, so that the water tubes are horizontal, the passage of the water being two-flow. By the provision of special ferrules on the water tubes of the coolers, single tubes can be readily withdrawn for inspection and replacement.

The coolers are built in two or more sections, each section being mounted on wheels or rollers and arranged to fit into guides in the floor and ceiling of the air-cooler chamber. Valves V (Fig. 18) in the water service enable a section to be isolated, and facilitate the withdrawal of individual sections. The handling of the latter, after being withdrawn, is effected by the means ordinarily available in the power station. Doors F and G (Fig. 18) are provided in the foundation air conduits to give access for inspection purposes, and to enable external air to be passed through the alternator when required. In the latter event, door G would be swung round so as to prevent further circulation of air through the cooler via the alternator when the latter is out of commission.

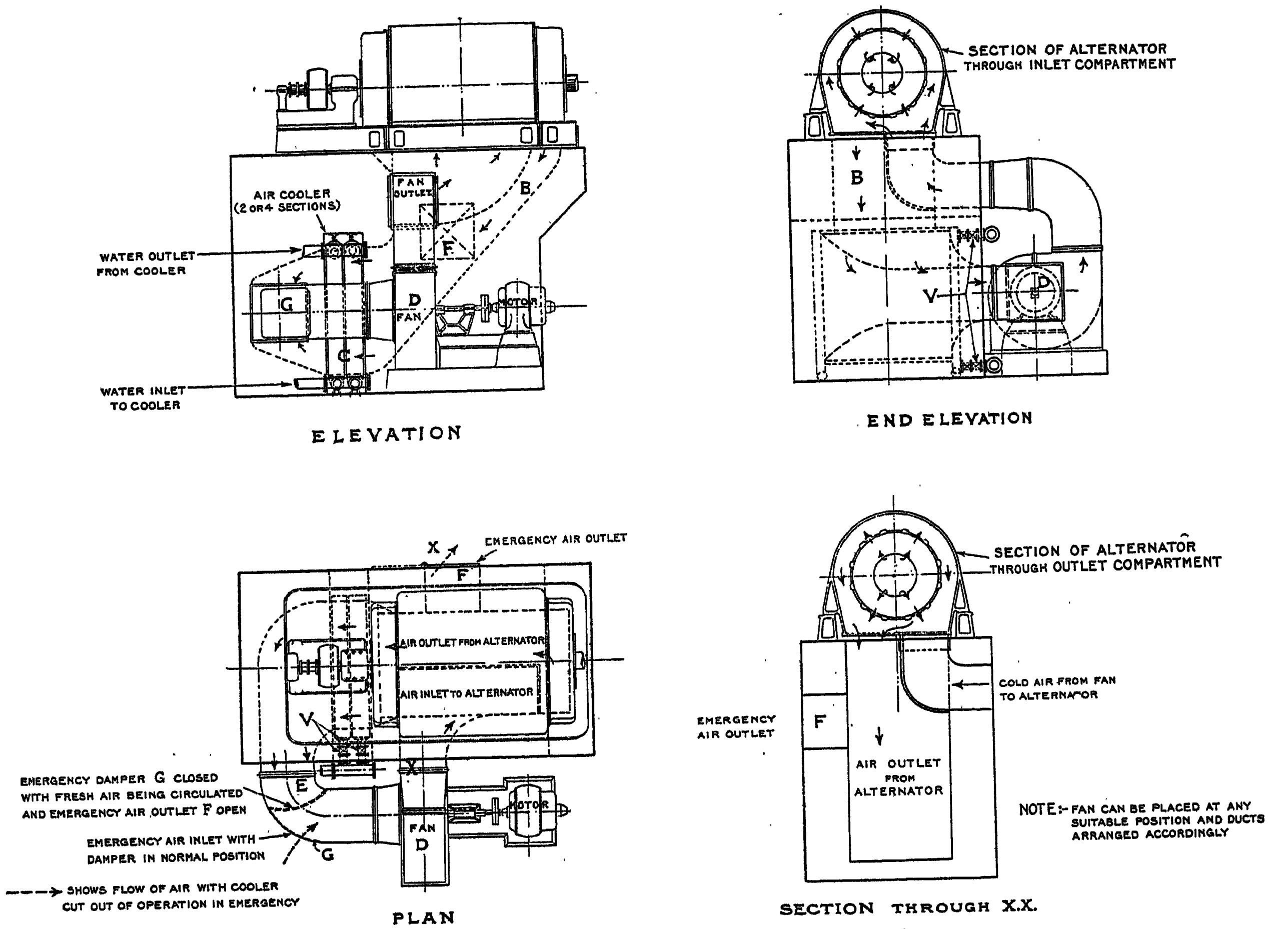


Fig. 18.

The water-box covers can be removed for cleaning the tubes without removing the cooler sections. The arrangement of the coolers in two or more sections enables any one section to be opened for cleaning, or to be removed for overhaul, while the alternator is in commission; the plant is operated meanwhile with the remaining sections, with somewhat increased air temperatures.

To prevent the possibility of the circulating water entering the air passages of the cooler, it is desirable that, wherever possible, the water tubes of the cooler

should be arranged on the suction side of the circulating water pump, so that the water pressure in them would be less than that of the circulating air, which would be drawn into a puncture or leaky joint, instead of the water being ejected into the air. The cooler can be tested periodically for possible leakages when the alternator is out of commission.

A knowledge of the quantity and temperature-rise of the water passing through the cooler affords a ready and accurate method of checking the heat losses of the alternator and fan.

Water cooling.—The use of a liquid cooling agent has always appealed to the designer of dynamo-electric plant. It was first applied to electrical machinery by Sir Charles Parsons in his original very high-speed dynamos, built during the period 1884 to 1889. The armature shafts of these dynamos were hollow, and cool oil was continuously pumped through to the outboard bearing. The innovation was subsequently discarded as relatively ineffective.

In 1904 or 1905, an alternator was built in which, as an experiment, water pipes were fitted in the radial ducts of the stator core, the dimensions of the ducts being similar to those of the customary air passages. Later, in 1905, the stator core of another alternator was cooled by a group of longitudinal water pipes, which passed through specially provided tunnels and were connected to water boxes forming the supports for the ends of the core. The most modern scheme* of water cooling used at present is illustrated in Fig. 19; the rotor is cooled by water which enters and leaves at the same end, giving uniform cooling throughout and avoiding the complication of having water connections at the coupling end of the rotor.

Thus, in Fig. 19, the water enters through the small stationary inlet pipe A, into the rotating tube B fixed to the rotor shaft. It passes along the central axis of the rotor radially outwards through the holes F, and returns through the longitudinal weldless steel tubes G placed immediately under the rotor windings, and so radially inwards, through the radial holes H, to the annular space J between the pipe B and the rotor body, exhausting through the perforated cap C into the water box formed in the end pedestal. The whole design is simple and free from danger.

The joints to the pipes G are made externally to the stator end shields, so that any leakage developing would be immediately apparent, and not dangerous to the alternator stator. The tubes are expanded into holes in the collars K machined from the rotor shaft, and the holes plugged. Any leakage along the tubes from the joints is thrown off by centrifugal force, and there is no danger of water coming into contact with either the stator or rotor windings.

The same water is repeatedly circulated through the rotor and is cooled in a separate surface cooler. The cooling water is normally supplied from the condenser circulating water system. The closed water system for the rotor is adopted, since it is found necessary to add

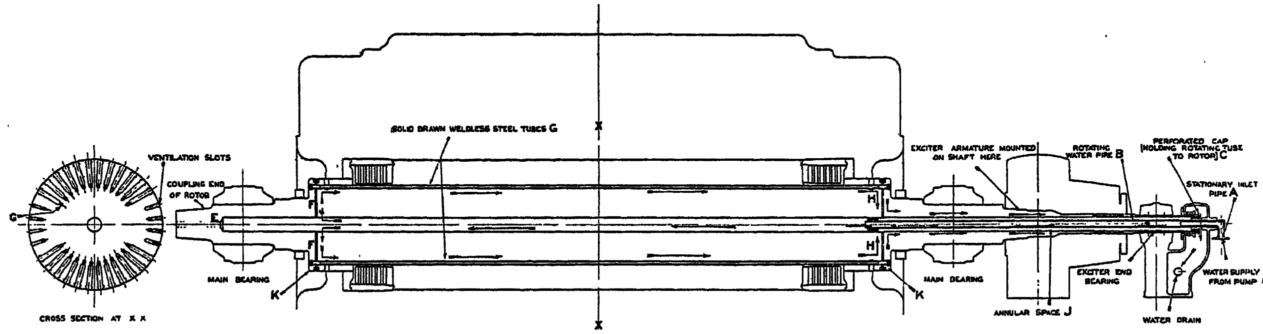


FIG. 19.—Longitudinal section through water-cooled rotor.

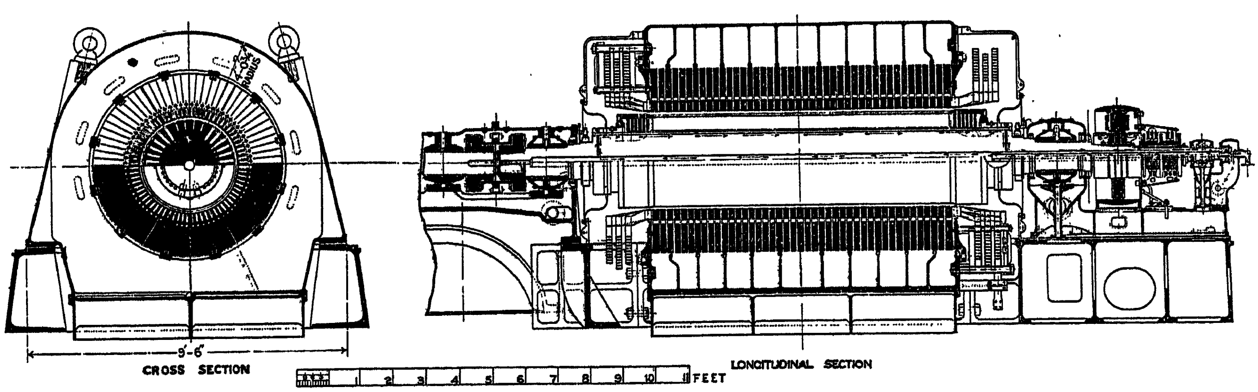


FIG. 20.—18 000-kVA, 5 750-V, 40-period, 2 400-r.p.m. three-phase alternator, 0·85 power factor.

* British Patent, No. 16 986/1914.

chemicals to the water in order to prevent corrosion of the water passages. Fig. 20 gives two views of an 18 000-kVA alternator with a water-cooled rotor, and it will be of interest to give a few details of this machine.

The output is 18 000 kVA, three-phase, 5 500–6 000 volts, 40 periods, at 2 400 r.p.m. The stator core has an internal diameter of 35 in., and a length of $108\frac{1}{4}$ in. There are 72 slots, or 12 slots per pole per phase, and each slot contains one conductor, so that there are 24 conductors per phase. The stator flux ϕ = 156 500 000 magnetic lines per pole, and the effective pole-arc being 29 in. (or 53 per cent of the pole-pitch) the mean density at the armature face is 50 200 lines per square inch. The peripheral speed of the rotor is 345 ft. per second, so that the centrifugal force of the material at the periphery is 2 700 times the force of gravity.

At the time the water cooling of rotors was adopted, it served a very useful purpose in providing an additional safeguard in the design of plant very much more advanced than any preceding it.

(6) Instability of Exciters.

Difficulties have been encountered the world over with the instability of exciters. This instability shows itself in two ways:

(1) The exciter voltage tends to creep when the alternator is running at no load, and it is difficult to steady the alternator voltage for synchronizing. This is due to the absence of saturation in the exciter magnetic circuit at the low exciting voltage.

(2) Reversal of the exciter shunt-field current and exciter polarity. If this occurs when the alternator

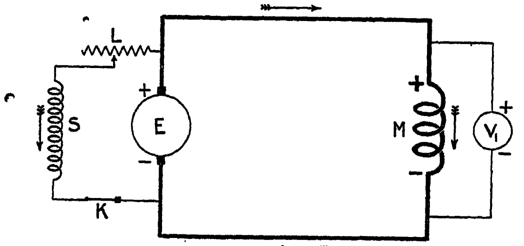


Fig. 21.—Shunt-wound exciter. Normal condition.

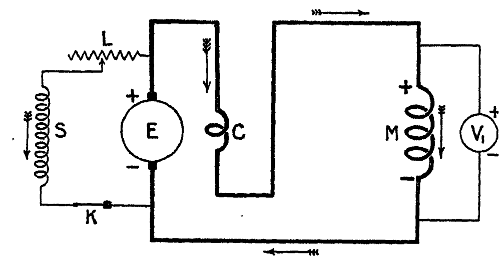


Fig. 23.—Compound-wound exciter. Normal condition.

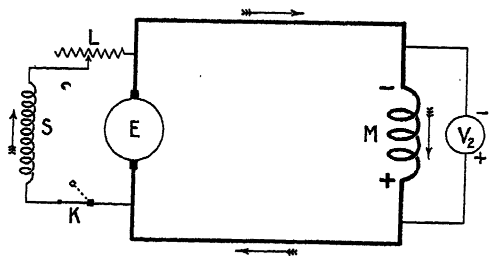


Fig. 22.—Shunt-wound exciter. Main field acting as a generator; exciter field and polarity reversed.

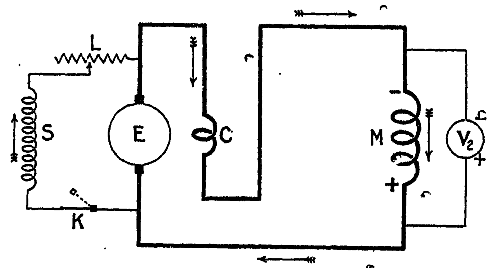


Fig. 24.—Compound-wound exciter. Momentary condition showing current in series winding overcoming effect of reversed shunt field current, main field acting as generator, and exciter terminal polarity reversed.

Figs. 21, 22, 23, 24.—Stability of exciters.

E = Exciter.
S = Exciter shunt field.
V_1 = Normal exciter voltage.
L = Shunt field rheostat.
K = Shunt field switch.
V_2 = Several times normal exciter voltage on sudden short-circuit.
C = Exciter series winding.
M = Rotor winding.

The output coefficient d^2l(r.p.m.)/kVA of 17 700 is lower than is usual for this size of plant. The increase in output for a given carcase, however, does not as a rule warrant the additional expenditure entailed in the manufacture of a water-cooled rotor. Only in special circumstances can water cooling be efficiently employed, e.g. in rotors where cooling water considerably below atmospheric temperatures is available. In using cold water, every precaution must be taken to avoid surface condensation of moisture from the air.

By the use of water it was possible to obtain a very useful indication of the losses occurring in the rotor body, including excitation losses and eddy-current losses under various load conditions. The actual power absorbed in the 18 000-kVA design at full output was 35 kW, the excitation loss being only 42 kW.

is running in parallel with other machines, the rotor drops back a pole-pitch and continues to give its load.

As a rule the effects of instability can be overcome by the provision of a main field regulator, which enables the exciter to work well up on the saturation curve. The introduction of the main field regulator is, however, not essential, as the regulation of an alternator can be readily carried out by means of a well-designed exciter field rheostat, with an exciter designed suitably for the lower voltages required for synchronizing the alternator. The use of a main field regulator also involves carrying the leads away from the alternator and introduces apparatus which is costly, and may give trouble and cause interruptions of supply. If no main field regulator is used, the main exciter leads can be carried straight from the exciter to the slip-rings and a main field

ammeter of the shunt type used. It is advantageous, therefore, to eliminate the main field regulator and to design the exciter to be stable over a very wide range of voltage.

The first-mentioned difficulty, evidenced by the creepage of voltage, has been overcome by introducing saturation gaps in the exciter magnetic circuit, by suitable designs of magnet frame and, in slotted armatures, by working the armature teeth at a high magnetic density.

So far as the author is aware, the phenomenon of the reversals of the alternator excitation current has not hitherto been explained, so that the following explanation may prove of interest.

In Fig. 21, E is the exciter coupled to the main field winding M, its shunt field being indicated by the letter S. It will be clear that if the shunt-field switch K is opened suddenly, the voltage generated by the exciter at E will rapidly collapse, but since this voltage is applied across the magnet winding M, which has a high self-induction, the current in the circuit EM does not fall so quickly. Consequently, the back electromotive force of the magnet M continues to supply the circuit EM after the field circuit S is broken, and the exciter voltage has dropped away, but, referring to Fig. 22, it will be seen that the polarity at the exciter terminals is actually reversed. With the exciter brushes set in the usual position in advance of the neutral, the exciter armature current has a demagnetizing effect on the exciter field and causes reversal of polarity; but if the brushes were rocked to a position behind the neutral, the current through E would have a magnetizing effect and would tend to preserve the original polarity of the field. Thus this type of instability could be remedied by rocking the brushes backward. The same remedy could be equally well applied by putting compounding turns on the exciter field. These turns must be directly compounding, and not demagnetizing turns. The reason for this is apparent, as when the field circuit S is broken (see Figs. 23 and 24), although the polarity at the exciter terminals is reversed the current in the circuit EM continues to travel in the original direction, due to the back electromotive force induced in the rotor windings, previously mentioned. It is found that only a very few turns of compounding are necessary to prevent reversal.

There is no objection to the compounding turns, but the rocking of the brushes backward is undesirable, since it is likely to cause sparking when the exciter is heavily loaded.

A similar exciter reversal has been repeatedly produced by the careless manipulation of the exciter field rheostat in power station operation. Consider the machine to be running preparatory to synchronizing. Too much of the resistance in the exciter field rheostat may accidentally be cut out, due to the slow rise of the alternator voltage. Consequently, the exciter current and alternator voltage rise a good deal above the normal required for synchronizing. The exciter field resistance is reinserted to neutralize this effect, and may cause the exciter voltage to collapse rapidly. This will have a similar effect to that occurring when the exciter field is entirely interrupted, and is even more likely to make the exciter field reverse its polarity than a complete interruption in the exciter field circuit, as, at the time, the back electromotive force of the rotor windings M predominates, the polarity at the slip-rings and exciter terminals is reversed, and, as the exciter field circuit is not broken, its current reverses also, and assists to build up the exciter polarity in the opposite direction. Fig. 22 illustrates the conditions obtaining.

Sudden changes of load and sudden short-circuits also cause reversals of the field polarity of the shunt-wound exciter. Under these conditions the voltage induced in the main field circuit is several times the normal exciter voltage, and therefore passes an increased reverse current through the shunt field. The compounding fitted to the exciter overcomes the difficulties entirely.

Experience has shown that this explanation is the correct one, and that the remedies adopted are satisfactory. The author has since made oscillograph tests, which entirely confirm the foregoing remarks.

(7) Eddy Currents in Rotors.

It has long been recognized that in three-phase turbo-alternators voltages are induced in the rotor, resulting in currents circulating in the rotor windings and body—more especially near the periphery of the latter. These voltages are induced in normal operation by flux pulsations, set up by variations in the stator current, or by periodic changes in the reluctance of the magnetic circuit. The resulting eddy currents increase the temperature of the alternator, lower its efficiency, and also, as is now known, may reach a magnitude sufficient to heat the metals to such a high temperature as to affect their mechanical properties.

The first indication of serious overheating was found several years ago when, in an alternator with a barrel rotor having a comparatively small air-gap between the stator and rotor, the coil-securing keys at the lagging edge of each pole were found to have been unduly hot. The heating was traced to the flux pulsations caused by the large ratio of width of stator tooth to length of air-gap; it was more pronounced at the lagging edge of the pole, as the flux of an alternator on ordinary loads is distorted by the armature ampere-turns in this direction, reaching a high density, with consequently increased local heating. Another difficulty is arcing. It is only comparatively recently that the voltages induced in the rotor body have reached such a value as to set up arcing. Signs of arcing were traced between adjacent sections of keys securing the winding coils in the slots, and between the spacer pieces fitted in the radial ventilating ducts on the plate type of rotor. The arcing was eliminated by the use of metal bonding-strips fitted under the keys, the centrifugal force of the coils forcing the bonding-strips into intimate contact with the keys.

Three years ago, during the annual overhaul of a large turbo-alternator, small cracks were found on the lips of the rotor caps where they were spigoted into the rotor body. This defect was found after two years' continuous operation.

A microscopic examination of the cap material indicated the presence of small amounts of slag, which, however, in themselves, were insufficient to cause the fractures. The fault developed on a water-cooled rotor. At the time it was suggested that, the body having been cooled to a greater extent than the cap, the radial clearances allowed in the standard construction of rotor without water-cooling were too small, and thus heavy

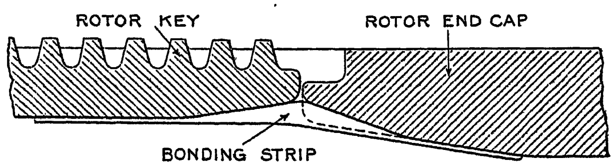


FIG. 25.

stresses had been produced in the spigot of the cap. The clearance was therefore increased. After the machine had been used for a further 12 months, the rotor was again removed for inspection, and it was found that the flaws had again appeared, on this occasion distinct signs of arcing on the cap spigot being apparent. The cap material was pitted and bore traces

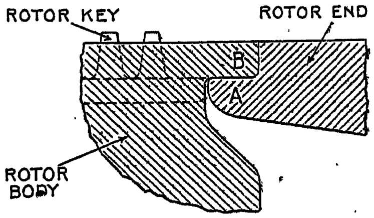


FIG. 26.

of local heating; it had become locally brittle, and the small cracks had consequently developed. After careful investigation it seemed clear that the eddy currents induced in the rotor during normal operation were insufficient to cause the arcing, but that very heavy currents might have been induced by sudden short-circuits on the alternator.

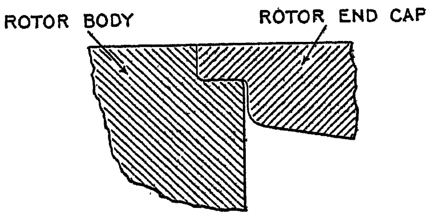


FIG. 27.

At the time this question came up for discussion, a 7 500-kVA, 6 600-volt, 3 000-r.p.m. three-phase alternator was being subjected to special sudden short-circuit and field-breaking tests at the Heaton works. It was decided to remove the rotor end caps, and to make a careful examination after the tests had been completed. The result was very convincing.

It was found that arcing had taken place between the caps and the rotor body in much the same way as

TABLE 2.

5 000-kW Alternator, Short-circuit Tests. Rotor Volts and Current, Exciter Volts and Field Current.

Pressure	Compound winding	Rotor pressure			Exciter pressure				Rotor current				Exciter field current				Time from s.c. to end of film
		Before s.c.	Maximum peak	At end of film	Before s.c.	Maximum peak	At end of film	Final by voltmeter	Before s.c.	Maximum peak	At end of film	Final by ammeter	Before s.c.	Maximum peak	At end of film	Final by ammeter	
volts		volts	volts	volts	volts	volts	volts	volts	amperes	amperes	amperes	amperes	amperes	amperes	amperes	amperes	seconds
2 000	In	8·5	− 29·7	+ 3·4	12·0	− 23·5	+ 3·8	—	25·5	69·4	+ 18·7	—	0·2	0·38	+ 0·05	+ 0·2	2·1
2 000	In	9·2	− 14·1	+ 5·4	—	—	—	—	25·5	87·5	+ 35·5	+ 24·0	—	—	—	—	1·6
2 000	Out	9·5	− 26·9	− 7·9	12·0	− 18·6	− 9·1	+ 5·0	25·5	179	+ 30·6	+ 17·5	0·3	0·91	− 0·25	+ 0·15	1·0
3 300	In	15·5	− 41	0	18·5	− 42·4	+ 1·6	—	42	256	+ 21	+ 27·2	0·4	1·09	0	+ 0·2	2·7
3 300	Out	15·0	− 28	− 16·8	18·5	− 26·5	+ 21·4	0	40·5	378	+ 20·8	0	0·43	Off film	− 0·60	0	1·3
5 000	In	23·5	− 59	1·5	27·5	− 36·4	− 11·4	+ 3·5	64·5	490	+ 46·8	+ 21·0	0·5	2·04	− 0·23	+ 0·1	2·1
5 000	Out	23·5	− 47	− 34·4	27·5	− 39·0	− 45·5	Reversed	64·5	725	− 43·5	—	0·65	3·23	− 0·93	− 1·0	0·95
6 600	In	37	− 104	− 18·5	—	—	—	—	100·5	930	+ 60	+ 20·5	—	—	—	—	1·4
6 600	Out	37	− 64	− 57·5	—	—	—	—	99	1 320	− 73·5	—	—	—	—	—	1·8

TABLE 3.

Rotor Circuit-breaking Tests.

Stator pressure	Compound winding	Rotor pressure		Time to zero	Rotor current		Remarks
		At start	Maximum		At start	Time to zero	
volts		volts	volts	seconds	amperes	second	
5 000	In	23·5	(Off film)	>1·9	66	0·032	Little arcing
5 000	In	23·5	— 245	>1·6	66	0·004	No arcing—clean break
5 000	Out	23·5	(Off film)	>1·5	64·5	0·050	Little arcing
5 000	Out	24·0	— 288	>1·6	67·5	0·060	Little arcing
6 600	In	37·5	— 284	>1·4	100·5	0·130	Considerable arcing
6 600	In	37·0	— 387	>1·7	99	0·047	Little arcing
6 600	Out	37·5	(Off film)	>1·25	105·5	0·052	Little arcing
6 600	Out	36·5	(Off film)	>1·7	100·5	0·065	Little arcing

TABLE 4.

5 000-kW Alternator. Exciter Field-breaking Tests.

Stator pressure	Compound winding	Rotor pressure		Time to zero	Rotor current		Time to end of film
		At start	End of film		At start	End of film	
volts		volts	volts	second	amperes	amperes	seconds
5 000	Out	24	— 8·0	0·075	66·6	53·5	0·54
5 000	In	24	+ 2·8	—	66·0	52·5	1·05
6 600	Out	36	— 5·0	0·11	99	66	1·0
6 600	In	37	0	0·16	99	69	0·9

TABLE 5.

5 000-kW Alternator, Short-circuit Tests. Voltage between Oil-thrower Rings on Rotor Shaft.

Stator pressure before s.c.	Peak pressure across shaft before s.c.	First peak pressure across shaft after s.c.
volts	volts	volts
2 000	0·27	10·6
3 300	0·39	13·4
3 300	0·40	15·5
5 000	1·23	26·2
5 000	1·16	26·2
6 600	0·82	22·6
6 600	0·68	22·6

had occurred in the water-cooled alternator. The principal arcing had occurred between the faucet on the rotor body and the cap spigot, also, to a smaller extent, between the rotor keys and the cap spigot. This was ascribed to—and later proved to be due to—the fact that, in the rotor under test, the keys were partially insulated from the caps by varnish. It was clear that comparatively high voltages were induced in the rotor windings and body by the variations in the value of the alternator main flux caused by:—

(*a*) The variation of currents in the stator when the stator windings were short-circuited.

(*b*) The interruption of the field current effected by a quick-break switch without a discharge resistance.

The remedy may be applied to the rotor in two ways:

(i) By short-circuiting, i.e. bonding the caps into contact with the rotor body, or by providing special short-circuiting rings at the end of the body.

(ii) By insulating the cap from the body so that currents will not stray into them.

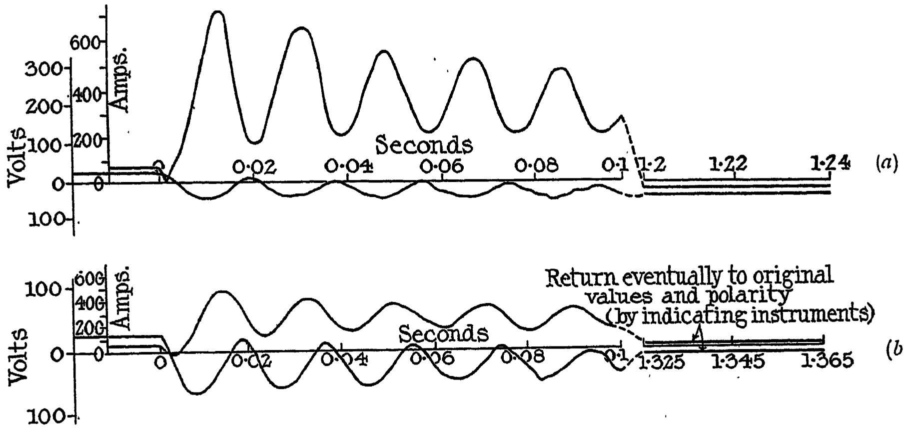


FIG. 28.—Rotor pressure and current under short-circuit conditions.
(a) Compounding out. (b) Compounding in.

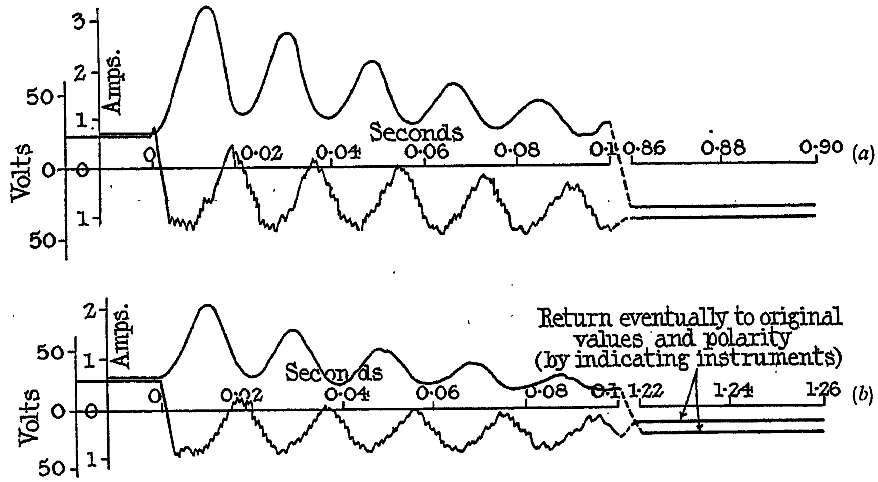


FIG. 29.—Exciter pressure and field current under short-circuit conditions.
(a) Compounding out. (b) Compounding in.

The latter remedy is the less satisfactory, and, moreover, more difficult to accomplish without radical departure from the best mechanical construction of the rotor. The first remedy was therefore adopted, and effected in a simple way by extending the bonding-strips above-mentioned from under the rotor keys to the caps. The modification was made on the 7 500 kVA alternator which had already been tested, but, as this plant was urgently required for shipment abroad and had already been considerably delayed owing to the earlier extended tests, it was not again placed on the test bed. Fortunately, an exactly similar machine was going through the shops at the time and all the tests were repeated, with the bonding-strips extended from the rotor body to the end-caps.

After a number of tests on this second machine, the rotor end caps were removed and the bonding-strips examined. A number of the strips were found to have fused at the points where the caps join the body, proving that heavy currents had been passing between the body and the cap; the caps and rotor body showed no marking.

Bonding-strips of larger cross-sectional area were then fitted, and the stator again subjected to severe short-circuit and field-breaking tests. After the removal of the caps, the bonding-strips were found to be intact, and neither caps nor rotor body showed any signs of arcing or local heating.

It is interesting to record that the two machines satisfactorily withstood more than 100 dead short-circuits during these investigations, some of which were made at 25 per cent above normal voltage.

The tests proved conclusively that, with suitable design, the eddy currents induced in a rotor during the worst conditions of short-circuit and of field-breaking can be readily carried by the rotor body, by the keys securing the exciting windings in position, and by the end-caps which support the ends of the exciting windings projecting beyond the rotor body.

Difficulty is experienced, however, in transmitting

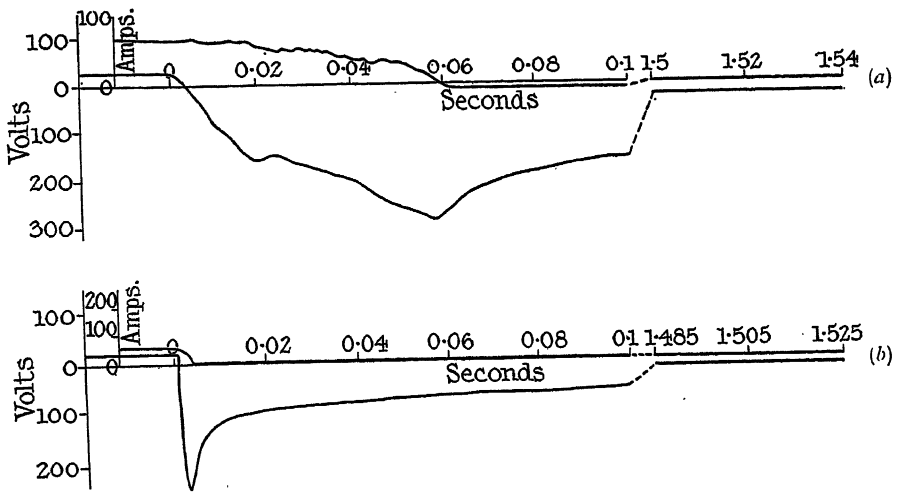


FIG. 30.—Rotor pressure and current on interruption of rotor circuit.
(*a*) Compounding out. (*b*) Compounding in.

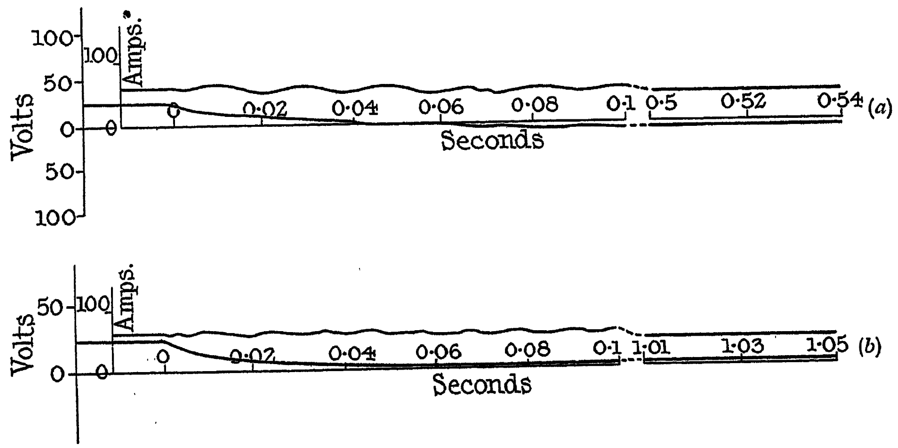


FIG. 31.—Rotor pressure and current on interruption of exciter field circuit.
(*a*) Compounding out. (*b*) Compounding in.

these currents between the cap and the body unless bonding-strips of large cross-sectional area are used. Such thick bonding-strips are objectionable as they occupy a great deal of space which would be more effectively filled by the exciting windings. A bonding-strip was therefore designed, having a locally increased cross-sectional area to fill the clearance space between the cap and the body as illustrated in Fig. 25, the caps and keys being shaped, if necessary, to take the additional copper area.

Referring again to the large alternator mentioned on page 453, the metal of the end-cap where cracked did not break away, and the reason for this will be clear from Fig. 26, which illustrates the standard construction adopted by Messrs. Parsons. The small pieces of metal which might have been broken off by the centrifugal stresses were held by the overhanging lip or faucet B of the rotor body. The fractures occurred at A.

The author has knowledge of certain rotors designed with the caps spigoted over the rotor body, where, in addition to other damage, pieces from the cap, each weighing approximately 2 oz., had broken away and caused damage to the alternators, necessitating their being rebuilt. At the time, various explanations were put forward as to the cause of the failures, but the author suggests that they may have been due to eddy currents. This is rather confirmed by considerations referred to later in the paper.

The rotors in question were spigoted as shown in

Fig. 27, a method which is perhaps more frequently adopted, both in England and on the Continent, than that illustrated in Fig. 26, which, however, the author considers to be the best practice.

(8) Oscillograph Tests.

Amongst the oscillograph tests on the 7 500-kVA, 3 000-r.p.m. alternator, the following records were made to obtain exact data of the instability of exciters, and of the voltages induced in the rotor:—

(a) Rotor voltage and current, exciter volts and exciter field current, with the stator windings suddenly short-circuited (see Figs. 28 (a) and (b), and 29 (a) and (b)).
(b) Rotor voltage and current with the main field circuit opened by means of a quick-break knife switch, without discharge resistance (see Fig. 30 (a) and (b)).
(c) Rotor voltage and current with the exciter field circuit broken by means of a quick-break knife switch (see Fig. 31 (a) and (b)).
(d) The change in voltage induced in the rotor shaft with the stator windings suddenly short-circuited. The oscillograph strip was connected to an oil-thrower ring at each end of the rotor shaft (see Fig. 32)).

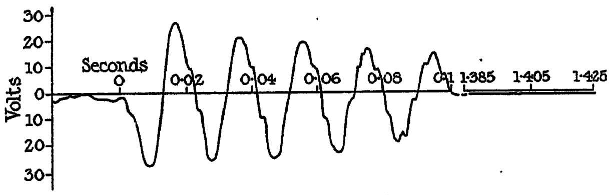


Fig. 32.—Pressure across rotor body at short-circuit.

The above tests were made with and without the exciter compounding turns in circuit.

Tables 2, 3, 4 and 5 give a short summary of the above and other tests, from which it will be seen that the voltages induced in the rotor windings on breaking the rotor circuit are very much more severe than those which occur on suddenly short-circuiting the stator windings.

It is impossible to give here complete records of the whole series of tests, but from them it was made very clear that suitably designed compounding turns fitted to the exciter poles are effective in preventing a reversal of the exciter magnet polarity when the alternator is suddenly short-circuited. This is also true when the rotor main field circuit is broken, when sudden variations are made in the exciter field circuit, or when sudden load variations on the alternator occur, as described earlier in the paper.

The author has been repeatedly requested by engineers to express an opinion upon the use of the quick-break field switch without discharge resistance in the main field circuit. In their view such a switch is essential in an emergency, in order to reduce the alternator voltage to a minimum with the least possible delay. In order therefore to obtain complete information upon this question, a series of tests were made to ascertain the conditions in the alternator when this switch is opened.

The voltages induced in the rotor windings and rotor body when the stator was suddenly short-circuited were 58·8 volts and 26·2 volts respectively. From comparison with tests (a) and (b) above-mentioned, it is reasonable to assume that the voltages induced in the shaft would be even higher than the latter figure under similar conditions on breaking the field by means of a quick-break switch. With this large potential difference between the shaft ends, it is obvious that heavy circulating currents must flow through the keys, shaft, and rotor caps.

As a result of these tests, it will be clear that, although every precaution may be taken in the design of alternators, heavy currents will circulate through the rotor on breaking the field circuit by means of a quick-break switch without discharge resistance. In the author's opinion it is inadvisable to subject the rotor repeatedly to these currents. It is recommended that the quick-break switch should be installed, but should be made to operate in emergency only, and should not be operated when tripping the alternators by hand from the busbars during normal operation. There will be no difficulty in arranging for this, and means can also be provided for testing the switch when the alternator has had its voltage reduced to a low value, or when it is unexcited.

In a paper such as this, it is possible to glance at only a few of the deductions made from experience and tests. It will be appreciated that although a great deal of work has been done to obtain more exact knowledge of what is really taking place in the operation of turbo-alternators, there is yet ample scope for research and greater improvements.

In conclusion, the author would express his thanks to Sir Charles Parsons, K.C.B., F.R.S., for his kindness in giving permission to publish the information contained in this paper, and to his colleagues on the staff of Messrs. C. A. Parsons & Co., Limited, Heaton Works, Newcastle-upon-Tyne, for their kindly criticism of the paper during its preparation.

Discussion before The Institution, 15 February, 1923.

Dr. S. P. Smith: One of the first things that strikes the attention of a designer on reading the paper is a statement on page 441 where the author pays tribute to the courage and initiative of consulting engineers who have encouraged his firm to put in a novel type of plant which resulted in a much larger increase of output. There is nothing more helpful to designers than to have such encouragement from consulting engineers. When a consulting engineer states that no tender will be considered unless the tenderer can show plants of a similar or larger size already working, the designer becomes very discouraged. The first point about which I wish to speak is in regard to ventilation. Designers of turbo-alternators appreciate that they have

here a machine through which it is possible to pass only a certain amount of cooling air. A more skilful designer may get perhaps 5 or 10 per cent more air through the air channels than a less skilful designer could, but the amount is strictly limited. Success in these large machines entails limitation of the losses. The author shows several ways in which this can be done, including a very ingenious and useful arrangement for reducing to a minimum the stator copper losses. I should be glad if he would indicate in his reply by what percentage the losses in the cable described with alternating current at 50 periods differ from those with an equivalent direct current. There is a point which manufacturers often overlook in the construction of large turbo-alternators. The weakness with the large turbo-alternator seems to lie at the present day more in the stator than in the rotor; and I do not think that sufficient attention has been paid to the elimination of hot spots in the machine. Though we try to get the factor of safety as high as possible, I think that if more care were taken in the construction of the stator core many breakdowns might be prevented. It is impossible to handle the laminations too carefully. If the shops take proper care in constructing the stator core, the iron losses in a turbo-alternator can be kept within 1 per cent of the output; otherwise they may well become 2 per cent. Large iron losses affect not merely coal consumption, that is, running cost, but also temperature guarantees and the life of the machine. Now that we use high-resistance silicon steel, we have to remember that the tools will not last so long as they did with the softer steel that was used years ago. It is absolutely necessary, therefore, to remove all rough edges found both the slots and the segments and to build a very rigid core. The author prefers to use a long core and small bore, but I think that if a larger diameter and shorter core were adopted, he might not find it necessary to use some of the special cooling devices mentioned. With regard to the rotor, it is known that when there is a hole in the centre the stresses are twice what they are when there is no hole. Is it worth while having a hole through the centre of the rotor in order to test the material and thereby get double the stresses? I think it is, but a test piece from the whole length of the rotor should be taken by cutting an annular ring. It is then possible to examine very carefully not only what the inside of the hole is like, but also the mechanical properties of the test piece. One firm has used aluminium instead of copper for the rotor winding. I doubt if a small diameter rotor would be so suitable for that purpose. Although the conductivity of aluminium is only 60 per cent of that of copper, the problem of the rotor end-covers becomes much simpler. In connection with the shape of the pressure wave, the author shows that it is possible to get a very smooth curve both between phase and neutral and between phases. Designers have long known that turbo-alternators present the best means of obtaining a practically pure sinusoidal voltage wave. There is, however, one danger which should be borne in mind. Though the tooth ripple may be too small to be seen in an ordinary oscillogram, there is a possibility of harmonics in the ripple which may cause trouble. For example, with 18 slots per pole-pair the principal harmonics would generally be the 17th and 19th. There is, however, a possibility that in addition there may be a 15th and a 21st harmonic, the danger of which is that they are multiples of three. The 17th and 19th, in a balanced system, have little effect on telephone wires a reasonable distance away, because, like the fundamental, their sum is zero at every instant; but whatever they are caused by, all harmonics, the orders of which are multiples of three, reach their maxima together; consequently when the neutral point is earthed the potential of the three lines is simultaneously raised and lowered with respect to earth, and currents can flow to and from earth at these frequencies. Therefore, where possible, the slots and winding should be arranged so as to avoid all trace of slot ripple and of harmonics, the orders of which are multiples of three. The means available for this are well known to designers.

Mr. W. M. Selvey: I propose to consider a few points in the author's subject, mainly from the point of view of operation. First I should like to suggest one or two details for the author's consideration. In Mr. A. B. Field's paper* which was read in 1915 this question of output was reviewed, and the question was then looked at from the point of view of kVA $\times$ (speed)^2. Might not that be a better way of viewing the subject? A comparison of that paper with the one under discussion shows what an enormous advance has been made. There are one or two details to which I wish to refer, the first being the laminated cable. This was quite a vexed question some years ago. The result of splitting up the formerly stiff conductors was always breakages of mica at the edge of the slot when a short-circuit occurred. Probably the major improvement that has been introduced (since the benefits of laminated conductors were then well understood) is the flexible mica insulation, which is very modestly announced in the paper. The difficulty in connection with insulation is the expulsion of the air. For insulation one requires something which will conduct heat but will not conduct electricity. That in itself seems a sort of contradiction in terms. Air, however, which is an extremely bad conductor of heat for various reasons, becomes at times a good conductor of electricity. I should like to hear whether there are any possible developments in this direction by the use of the newer types of insulation which are being made, I think, from solidified colloids. It seems as though some of these new types of insulation may entirely replace mica. The dielectric strength is quite good and they certainly have a more mechanical nature. Curiously enough, the difficulties in operation arising to-day are generally due to current. Anything which decreases current, whether in a cable or machine, is of assistance. I am surprised that more use has not been made of the information given by Mr. Welbourn in connection with his visit to Italy, with regard to the very successful alternators which have been running for four or five years generating current at 30 000 volts. That increase of pressure will, of course, diminish very greatly the amount of copper used.

* "Some Difficulties of Design of High-speed Generators," *Journal I.E.E.*, 1915, vol. 54, p. 65.

On page 447 there is another small point requiring elucidation with regard to the two power stations a mile apart. A discussion is wanted on that subject; it is a question of distance and earth resistance. How far apart are linked power stations to be put before one must earth both? I have that actual problem before me at the present time. There must be some limiting distance. If one goes far enough the earth resistance will be high. I suggest that the solution in some cases may be the earthing of one station through a limiting resistance and arranging an automatic switch so that any rise in pressure at that station which shows that it has become disconnected from the other station, shall cause any limiting resistance to be short-circuited. It is news to me that circulating current, which is wattless, influences the ordinary induction type of meter. One can quite understand an ammeter giving a higher reading, but this case is stated as a definite transference of "load," and I cannot understand the ordinary integrating meters in the power station showing transference of load due to circulating currents. On page 449 there is the statement: "In this type of filter (wet-air) it is possible not only to clean the air, but also to lower below that of the surrounding atmosphere the temperature of the air entering the machine." That is only possible when the air is being drawn from the engine room and the water is at the temperature of the outside air; but is this generally the case? It is quite a number of years since it was considered good practice to draw air from inside the engine room, because that air is generally laden with oil vapour. The latter caused serious trouble and the breakdown of a very large machine in the North due to accumulation of oily mud on the windings. I have made many experiments on the subject, and I have been unable to find any appreciable air-cooling or humidity effect when the air and water are at about the same temperature. It is very difficult to obtain any increase of humidity by simply forcing the air through a spray. If humidified air is required, steam must be added to it. I think, therefore, that the statement made by the author ought to be further investigated. I have made a large number of experiments on the carrying-over of water, and I probably obtained hints from the author's work. In an air-filter with which I experimented, I could alter the quantity of air over a large range. By means of winding a coil of ordinary double cotton-covered wire on a conductor, placing it in the filter outlet and then noting the insulation resistance, it was perfectly easy to see if and when water came over from the filter. The author has not mentioned the very interesting fact that in these large machines with long rotors and parallel ducts the pressure necessary to force the air through the alternator has been much increased. In the early days it was something under 1 inch head of water. Then it increased to 3 inches and 6 inches, and I have been informed that in some cases it may be increased to 15 inches, so that its provision becomes a serious matter. From that point of view, I am entirely in agreement with the author that it is necessary to pay attention to the efficiency of pumping the air, and that it can only properly be done by an external fan. As regards the water cooling and the deductions made from it as to heat losses in the rotor, I feel that only a small proportion of the heat from a rotor coil can be removed by a tube immediately underneath it, and a good deal of the heat must in any case be dissipated from the surface of the rotor. Although the author is guarded in his remarks, he commits himself to certain figures. In any case it must be remembered that the chief heat resistance is in the mica windings, and the fact that the bottom of the slot is cool is no guarantee whatever as to the copper temperature. It seems that there is something rather doubtful in the conclusion at which the author has arrived with regard to the field-suppression switch. Must we suppress the field for the purpose of limiting the voltage on short-circuit, and thereby injure the rotor? It seems to me unsound to have an emergency switch which must not be used on ordinary occasions, because its use will produce damage. If there is anything in the apparatus or plant which can be damaged at the will of the operator it should be altered.

Mr. G. W. Partridge: I should like to know the author's opinion regarding the limit of pressure on such a machine as he describes, running at 3 000 r.p.m. with an output of 25 000 kVA, which is referred to in Table 1. Of what class of metal are the rotor caps mentioned at the foot of page 442 made? In many respects most of the troubles enumerated by the author are of long standing and have been overcome by contractors in the present-day design of such machines. The company with which I am associated has supplied single-phase current to the Brighton Railway for the past 14 or 15 years, and many of the troubles to which the author has referred, particularly those connected with the rotors, were experienced by my company, but the difficulties have been overcome by the designers of the generators. I think the author will agree that a single-phase supply to a railway, accompanied as it is by a great number of direct short-circuits, is a very severe test for any a.c. machine. It might be desirable in the future to subject a.c. generators to a test of a limited amount of single-phase current with the object of deciding whether the rotor defects referred to in the paper actually take place. In the design of stator illustrated, which shows straight conductors in use, twice the number of joints would have to be made in such stators as compared with straight conductors with the bent ends used by other contractors. With regard to the circular laminations, I should have thought that rectangular bars, made up in a certain way to be practically free from eddy currents, would have been a very much stronger proposition. Referring to the stator in Fig. 11, it seems that the overhang of the coils is excessive and would certainly be reduced if the design of straight bar with the bent end were used. Another important point in connection with Fig. 11 is that the coils are not supported where they leave the slots. This is, I think, very important. With regard to the tunnel formation of winding, this is really a reversion to an old system and seems to possess certain disadvantages. First, the large number of joints to which I have already referred, and secondly, the difficulty of getting a good fit between these bars and the stator so as to overcome the difficulty

of the air space round the coil, which would in turn cause a brush discharge difficult of elimination and likely to give trouble. In the construction shown the bars would have to be driven in from one end of the stator. Another point is that if any short-circuit or welding took place between the copper and the iron it would be absolutely impossible to get at the coils or even to examine them without dismantling the whole stator. I entirely agree with the author that it is a very difficult matter to design a machine and make ample allowance for expansion of the copper in both the rotor and in the stator. In fact, in a modern high-speed machine it is more difficult to keep the copper inside the insulation than it is to keep the current. In Fig. 11 there appear to be no through bolts for holding the stator iron. From my experience it is necessary that such bolts must be used if the core is to be held rigidly. Of course the nearer the through bolt is to the flux the more rigid the stator can be held, from a mechanical point of view. On the other hand, the nearer the through bolt is to the flux the greater the trouble due to eddy currents, from an electrical point of view. We have machines with such through bolts of non-magnetic material insulated by mica from the core plates, and these have been running quite satisfactorily as either single-phase or three-phase generators for about 8 to 10 years. The separate motor fans shown by the author are, I think, another weak link in the generator system. There are enough weak links already, as we know to our cost; and as the fan will probably be running at the same speed as the generator, i.e. 3 000 r.p.m., I cannot see much advantage in having a separate fan. I am in agreement with the author that the closed air system is preferable for large machines. I should like to ask him if he has ever considered two-part stators, in which the joint might be at right angles to the path of the magnetic flux. It seems that such a machine would possess some advantages, particularly when, owing to the high speed, such machines are of great length. Eddy currents in the rotor are an old trouble, particularly in single-phase work. Even in three-phase work one often meets with it when a short-circuit occurs between any two phases. On more than one occasion I have seen rotors of three-phase generators broken down through this cause. The provision of bonding strips fitted under the rotor keys has been more or less in use for a great number of years. In such a construction it is, of course, necessary to allow ample room for expansion. As regards the general design of rotors for these high speeds, it seems to me that the manufacturers have studied the design of the stators more closely than that of the rotors. In the old days when four-pole and six-pole machines were in use the rotors very seldom went wrong, and it was nearly always the stator which developed the fault. The following precautions should be taken in the design of these high-speed rotors: (1) The movement of the field coils should be limited as much as possible and every precaution taken to prevent damage to the insulation caused by movement either from centrifugal force or expansion; (2) any bonding strips or short-circuiting rings should be given room for expansion; and (3) the insulating blocks holding the end-coils in place should be of a material which cannot shrink or warp due to heating. With regard to the author's remarks on page 453 as to the reversals of field polarity in exciters when the generator is short-circuited, about 9 years ago I showed the effects of a large number of short-circuits on alternators. These effects were: (1) The excitation voltage was reversed; (2) the field current was increased about $2\frac{1}{2}$ times; (3) the presence of alternating current in the field; (4) this alternating current was of twice the periodicity of the main current. Very little trouble has been experienced due to exciter instability, probably because special care was taken to saturate the pole shoes at low excitation, thereby giving to the exciter characteristic the proper shape and curvature.

Dr. W. M. Thornton: One of the most interesting things in the paper is the wave-form of the 18 750-kVA generator (see Figs. 12 and 13). Those who have had experience in taking wave-forms over a wide range of machines know how difficult it is to obtain and maintain a sine wave on load. These are the best I have seen for a large machine. The problem most prominent at the present time before those responsible for large units is how best to kill the rotor field after a short-circuit,

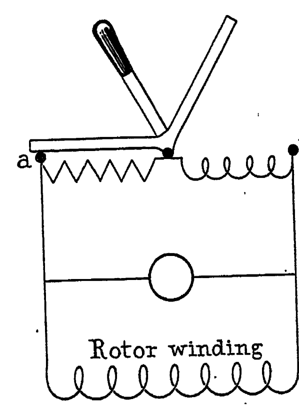


FIG. A.

or for any other purpose. An important paper by Mr. R. E. Doherty on "Exciter Instability" appeared in the *Journal of the American Institute of Electrical Engineers* (1922, vol. 41, p. 731). The best remedy so far is to compound the exciter, and the oscillograms of Figs. 28 to 31 show how useful this is. There is a further remedy which does not appear to have been tried, that is, to use a small buffer resistance in series between the rotor field and exciter. The object of this is to prevent the voltage induced in the rotor circuit by the stator ampere-turns from reaching the exciter terminals and so reversing its field. If the exciter pressure is, say, 25 volts and the rotor current 65 amperes, the resistance of the circuit is $0 \cdot 38$ ohm. On short-circuit the rotor current rises to a mean value of 300 amperes with the compounding turns in circuit. The rotor voltage is therefore $(300 \times 0 \cdot 38) - 25 = 89$, if the exciter terminal voltage does not rise. If now a resistance of $89/300 \doteq 0 \cdot 29$ ohm had been in circuit, all the induced rotor voltage would have been absorbed in that. There would have been no undue rise of pressure on the exciter and no tendency to reversal. Such a resistance would mean that the normal voltage of the exciter would have

to be $65 (0 \cdot 29 + 0 \cdot 38) = 43 \cdot 5$ for the same rotor current. There would be a constant additional loss of $0 \cdot 29 \times 65^2 = 1\,220$ watts if the resistance has to be kept permanently in circuit. Whether this is worth losing is a question for the supply company and not the designer. The author discusses the effect of breaking the exciter field instead of the rotor circuit, but there is no need to break it. An old arrangement would seem to be suitable here (see Fig. A). If the exciter field is connected not to the terminals directly but to a change-over switch, all that is necessary to kill the rotor field is to short-circuit the exciter field by throwing the switch over from a to b. The field then dies down in about 0·07 to 0·10 second. The non-inductive resistance then provides an alternative path to the armature and lessens the vicious momentary sparking which occurs at the commutator. In this case, however, compounding turns on the exciter would prolong the effect. I should like to emphasize the great improvement that has been made of late years in the mode of bringing out the end connections on the stator so that a machine of the largest size can be short-circuited without any ill effects. I recently had occasion to take part in the preliminary tests on the short-circuit behaviour of a 6 000 kVA Parsons generator. We made nearly 100 dead short-circuits at all excitations with the sole effect of clearing the machine of dust. This led me to make the suggestion in the discussion on Mr. Kuyser's paper that the best way to free modern generators from dust in the ventilation ducts is to short-circuit the machine deliberately at reduced excitation. Instructions might be given to short-circuit each machine on some Saturday once a month, say No. 1 machine at 12.30 when the load comes off, No. 2 at 12.45, and so on. I think that the time is not far off when this will be a serious proposition at any excitation. It could be safely done with any recent Parsons machine of the same construction, and the author's 100 short-circuit tests on two 7 500 kVA machines show that the machine on which we experimented was not at all unusual.

Mr. H. W. Taylor: In regard to machines made by the firm with which I am associated, developments have been in some cases almost parallel with, and in other directions divergent from, those of the author. Almost parallel development has resulted from our both adopting an ideal of using the best materials, but at as low a stress as possible. This has led at higher speeds to machines with relatively small diameters and long lengths. This again has given rise to problems of ventilation; on rotors water cooling has been tried and in stators radial ventilation in compartments has been adopted. The arrangement for water cooling has, however, been slightly different from that shown in Fig. 19. Fig. B shows how passages have been provided by small holes drilled some little distance below the winding slots. In the long rotor in which this scheme was tried the holes were drilled with no difficulty by a firm of experienced gun makers. This construction admits the use of the deepest possible slot containing the largest possible amount of active material, the holes being placed in the central core of the rotor where the stress is relatively low. Fig. C, showing the method of ventilating a large 3 000 r.p.m. alternator when used in conjunction with an air cooler, may be compared with Figs. 16 and 18 in the paper. In machines of this character, auxiliary fans are necessary. Fig. C shows that the hot air from the machine is conducted through ducts in the foundations to the external fan, which, because of its inefficiency, adds further heat to it. The cooler is placed between the fan and the air opening to the turbo-alternator, so that the air enters the alternator at a temperature as low as is consistent with the temperature of the water in the cooler. A feature in which development has been divergent from that of the author is in regard to the form of the stator windings. The type sometimes described as the two-layer basket form of winding has been developed and used continuously since the building of turbo-alternators was commenced many years ago. It is felt that in this type of winding, diagrammatically

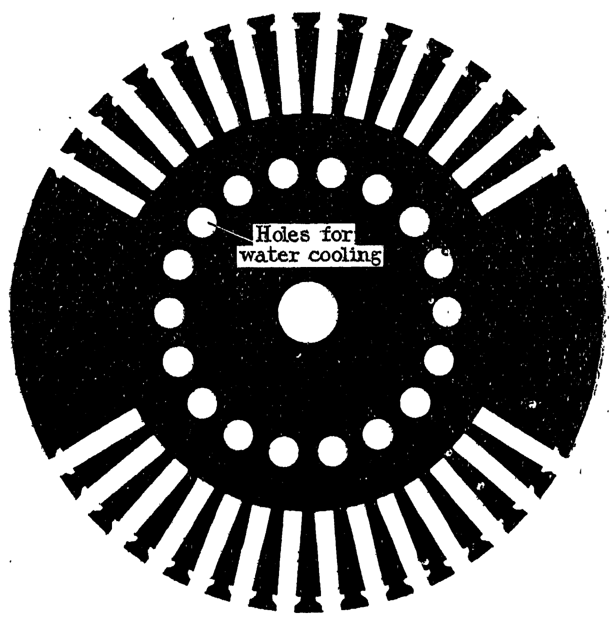


FIG. B.

indicated in Fig. C, the shape and position of the end coils are such that no appreciable stresses are produced during short-circuits, with the result that these windings require a minimum amount of supports and clamps. In regard to switching on the rotor circuit, the following points seem to me briefly to sum up the situation: (1) If the rotor field circuit is opened while the machine is under normal operation, there is undoubtedly a high voltage-rise in the windings. (2) Normal service does not require the rotor circuit to be thus suddenly opened, and can be met by withdrawing the source of supply in other ways. (3) When the stator windings are short-circuited, it is possible to open the field circuit suddenly without an increase in voltage in the rotor windings, because the short-circuited stator windings are in good mutual induction with the rotor windings. (4) Under these circumstances, although the rotor current quickly disappears, the current in the stator winding fault is not immediately suppressed, as the

flux of the machine is maintained until the stored energy represented by it has been absorbed in the short-circuited stator windings. The opening of the rotor circuit, therefore, does not simultaneously suppress the fault. (5) This being so, a scheme which withdraws the source of supply from the rotor circuit without opening it would seem to meet the conditions for both normal and emergency operation. A switch which effects this by short-circuiting the slip-rings has been developed and has already been described and illustrated in the *Journal* (1922, vol. 60, p. 773).

can flow in the rotor are those tending to maintain the alternator flux, and it may be an advantage to consider these from the point of view of the energy available. If the field switch is opened without a discharge resistance (really an infinite discharge resistance) the whole of the stored energy of the magnetic field is dissipated as heat in the rotor body, the amount of energy available in the case of a 15 000 kVA 3 000 r.p.m. machine being sufficient to melt about 4 or 5 cm^3 of copper originally at the working temperature of the machine. When using a discharge resist-

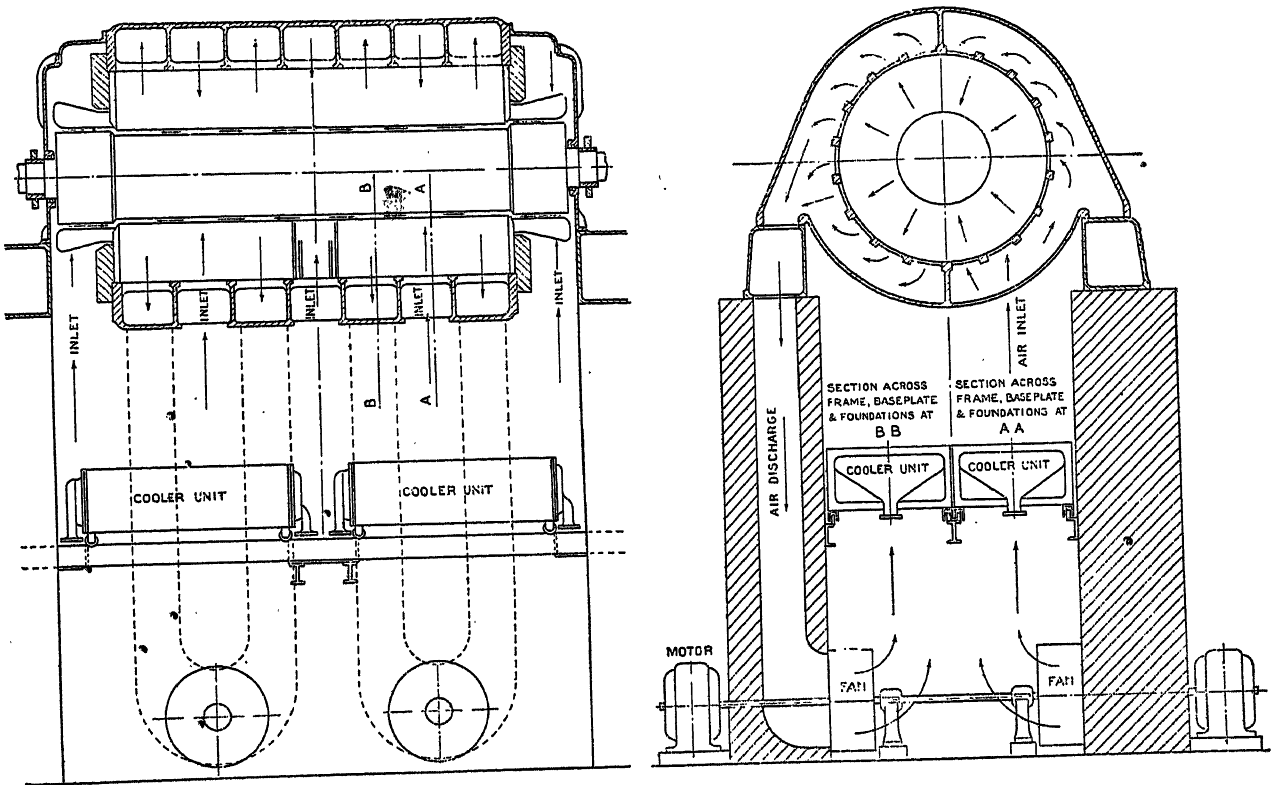


FIG. C.

Mr. N. B. Hill (*communicated*): In Section 4 the author suggests that there is a marked increase in inherent reactance to be expected from the use of closed stator slots. This is probably correct while considering the reactance at the normal current of the machine, but as the iron bridge would become saturated with a stator current much lower than the instantaneous short-circuit current of the machine, the maximum advantage of a closed slot over an open slot appears to be that represented by the extra leakage flux corresponding to the saturation value of the iron. In one or two cases that I have calculated, this has meant that the increase to be looked for in the reactance on instantaneous short-circuit due to the use of a completely closed slot is only of the order of $\frac{1}{3}$ per cent. When using a quick-break field switch, the author anticipates (see Section 8) the production of a voltage between shaft ends similar to that shown in Fig. 32. If the outboard pedestal is insulated the only currents which

ance the energy is dissipated as heat in two circuits in parallel, the rotor winding and discharge resistance forming one circuit, and the rotor body, wedges and end caps the other. The energy will divide between the circuits inversely as their resistance. Mr. Kuyser * gives the equivalent resistance of the rotor body circuits as five times that of the field winding, and I have confirmed this figure by a different method of measurement. If we therefore short-circuit the slip-rings (zero discharge resistance) it would appear that only one-sixth of the stored energy of the field would have to be dissipated in the rotor body circuits. Although the question is not so much one of total loss, due to the circulating currents, as of the local loss at the junction of the rotor body and wedges with the end caps, I think it is well to keep the total loss in mind, and I agree with the author that it is good policy to use the quick-break

* "Protective Apparatus for Turbo-Generators," *Journal I.E.E.*, 1922, vol. 60, p. 761.

switch without discharge resistance in cases of emergency only. If this switch operates only when the protective gear operates, and the alternator field is normally destroyed by opening the exciter field switch, we ensure the quickest possible destruction of the field under fault conditions without normally subjecting the rotor to more severe conditions than would be obtained by short-circuiting the slip-rings.

Mr. J. H. Shaw (*communicated*): On pages 449 and 450 some useful information is given regarding the use of closed-circuit coolers, and the author refers to the pioneer installation at the Battersea Electricity Works. I do not think, however, that sufficient credit has been given to the patentee, Mr. Thompson, of the Battersea Electricity Works, for this achievement, and I think that few engineers know how successful this plant is in operation. It was designed early in 1918, before the plant at Blaydon, and has to-day many advantages over similar systems with which I have compared it. Some years ago I inspected the plant at Battersea and was informed that when planning the installation of their 5 000-kW alternators they could not find space for dry air-filters, and were not kindly disposed towards the wet type on account of the risk to the insulation of the machine. The chief engineer, together with his chief assistant, Mr. Thompson, set to work to devise some alternative system of cooling, and they conceived the idea of continually circulating the enclosed air, thus avoiding any filtering whatever, and using the condensate as the cooling medium, thus eliminating any necessity for cleaning the tubes. Several large makers of alternators to whom this system was explained considered it was not practicable, and as the necessary data for designing the apparatus were not available Mr. Thompson constructed experimental plant for the purpose of ascertaining the air and water velocities, tube spacing, etc. The Battersea design, as regards construction, compactness and efficiency, has justified the trouble taken, and is protected by letters patent. Practically all the cooling is effected by the condensate, the cold "make-up" water only being introduced on heavy loads or when the vacuum is poor. The cooler has been in service continuously for about four years and has not yet had to be cleaned; this would not have been possible with circulating water as the cooling medium. The working of the plant has not been interrupted, and the cooler efficiency has been maintained. Apart from this, the heat is recovered from the ventilating air, resulting in the condensate temperature being raised about 11 degrees F., which amounts to nearly 1 per cent of the total heat in the steam. The cooler was constructed to the Battersea design by Messrs. Babcock and Wilcox with plain tubes expanded into headers, sectionalized so as to reduce cost of manufacture and for ease of transit and erection, and mounted on rollers to facilitate removal if required; it has remained perfectly water-tight since erection, thus dispelling any fears as regards water leakage into the air space. Another good feature of this system which will appeal to the operating engineer is the provision of thermostatically-operated air doors which permit of the alternator being cooled from the outside air should the enclosed air reach a predetermined temperature due to any cause other than electrical faults in the machine, in which latter case these air doors will remain closed. In the description of other systems it is stated that a horn or whistle will be blown and coloured lights displayed, but it is better to do this work automatically and remove the human element, especially as one knows that when things go wrong there is plenty of work for the operatives to attend to, and one does not wish to add further noise and coloured lights. It is of interest to note that the five 40 000 kW sets at Gennevilliers are cooled on the same system as that used at Battersea, and with coolers of similar design, and on account of its economy and efficiency this system is being adopted in connection with many other large plants. It is very pleasing to note the absence of noise due to the alternators being entirely enclosed, and the temperature of the engine room is more comfortable for the operatives, particularly during the summer time. I understand that the letters patent referred to cover the use of gases which will not support combustion and which at the same time improve the efficiency of the heat transmission, and I believe that experiments are being made with carbon-dioxide gas. I feel that Mr. Bond and Mr. Thompson are to be congratulated on their courage in designing and installing this cooler, and that due publicity should be given to their pioneer efforts.

Mr. J. Shepherd (*communicated*): The paper gives a clear statement of the difficulties with which designers have to contend, and a brief review of many different attempts to overcome them. All credit must be given to the earnest desire of manufacturers to produce sound and satisfactory machines, but when all these efforts have been made the fact remains that turbo-alternators are not as satisfactory as either makers or users desire. Messrs. Parsons and Co. are the pioneers of water-cooling applied direct to the body of the rotor, and the British Thomson-Houston Co. are now manufacturing rotors similarly cooled. Indirect water-cooling of the ventilating air is becoming universal. If water-cooling is to be accepted as necessary, the general design of turbo-alternators should be considered from a new view-point, as other inherent difficulties can then be solved at the same time. With air-cooling, the stator and rotor cores must be constructed with numerous air-passage ways, and these of necessity result in a weak structure with weakly supported stator teeth and coils. Let any engineer examine and consider the deplorable mechanical weakness of a thoroughly laminated stator coil as now constructed, various examples of which are shown in Fig. 8 of the paper. The component parts are held together only by the insulation surrounding them, and, due to the method of stranding, there must be slackness between the parts, with continuous vibration due to the alternations of current, resulting in the gradual disintegration of the insulation. Further, all the mechanical forces from the turbine must be transmitted by the insulation, which must also withstand the tremendous hammer-like blows on short-circuits. The same remarks apply, of course, to all laminated bars. As strength cannot be obtained within the coil it must be applied without, and the logical solution is a winding slot continuous throughout the entire length of stator windings including the end connec-

tions, and this positive and continuous support can be given if the water-cooling be applied directly instead of indirectly. When this is done the stator structure can be solidly constructed with the equivalent of solid rotor teeth, thus eliminating the trouble which the author and other designers have experienced from cut and broken teeth. Adequately strong supports, in the shape of cooling devices with separate and adjustable water supplies to each, give a ready and definite means, which at present we hardly possess, of detecting local heating. On the other hand, we require most positive assurance that we possess means of constructing the water-cooling devices without risk of water leakage. The internal water pressures in the rotors are usually approximately 800 lb. per sq. in. and upwards, and both Messrs. Parsons and the B.T.H. Co. successfully constructed water-cooled rotors for these pressures. The cooling devices in the stator would be subject to internal water pressures under 100 lb. per sq. in., and we possess methods of welding and electrical deposition of metals which would allow any desired thickness of metal to be built up at the joints, the only parts which need give anxiety. All the present papers by turbo-alternator designers lay stress upon the difficulties with which they must contend, and to me they clearly demonstrate the limitations of air-cooled machines and the need of an entire change of design to allow mechanically strong machines to be constructed. The problem is by no means one of air-cooling versus water-cooling, but the ever-pressing necessity of building robust and more reliable alternators.

Mr. J. Rosen (*in reply*): I agree with Dr. Smith that every attention should be paid to limiting the losses in turbo-alternators, and to improving the ventilation. The actual additional losses due to the eddy currents in the helically stranded conductor are extremely low, being less than 1 per cent of the I^2R loss for the equivalent direct current. As far as the core is concerned, makers are fully aware of the precautions necessary in the building of a stator core, and every practicable care is taken.

I cannot agree that short rotors with larger diameters and therefore higher peripheral speeds are preferable to long rotors running at well-tried peripheral speeds, as the stresses in the former are increased beyond those which experience has proved safe.

In the past, axial holes have been trepanned throughout the whole length of the central axis of alternator rotors for the purpose of testing the material, and in some machines the metal removed was weighed to make sure that no blow-hole or clink was present. In every rotor where such a hole is drilled, the surface of the bore is carefully inspected for flaws, by means of special optical arrangements.

Theoretical investigation of the simplest case of rotational stress—namely, in a thin, flat disc—indicates that a pinhole at the centre makes the hoop stress at the periphery of the hole double what it would be at that point if there were no hole. In practice, however, there is evidence that a small hole through the centre of a rotor shaft has no such extreme effect upon stress distribution, but modifies it to a much less extent than is indicated by purely theoretical consideration. It can be taken for granted that the material will yield to some extent and ensure that the stresses become more uniformly distributed, so that the final maximum stress (in the neighbourhood of the hole) will not be actually very much greater than that in a shaft without the hole. In fact, in view of the difficulties which have recently been experienced on alternators in this direction, engineers are now asking for holes to be drilled in the centre of the high-speed shafts for the reasons above mentioned. I have recommended this procedure for large shafts since 1914, and it has been adopted in Parsons alternator rotor shafts intended for peripheral speeds in excess of about 350 ft. per second.

The slides shown by Dr. Smith are interesting, but a parallel cap for supporting the rotor windings can be obtained with a rotor running at a lower peripheral speed without having to resort to aluminium for the windings; in such a design there is no necessity to have the steep taper on the cap. The use of aluminium for the rotor windings has been a subject of peculiar interest to designers of high-speed alternators, but up to the present time its use has not proved a commercial proposition. The difficulties due to harmonics in the wave-form are appreciated, and, as indicated by the typical examples in the paper, this question has been thoroughly investigated.

In reply to Mr. Selvey, the flexible insulation has been used now for the past 10 years with unqualified success, but investigations are continually going forward to improve this insulation and to provide an even better solution of the insulation problem. A description of the investigations into the qualities necessary for insulation suitable for high voltages and for use in turbo-alternators would provide sufficient material for a separate paper, and could not be dealt with as fully as I should have liked in this paper. I have experienced no difficulties with the breaking of the mica at the edge of the slots when short-circuits occur; and with the design in question there is no tendency for the conductors to separate on a heavy short-circuit and burst the tube. I have dealt with the other questions on insulation in reply to Mr. Partridge.

Mr. Selvey appears to be under some misapprehension on the question of the cooling of the air passing through wet air-filters. As a rule in this country the air before entering the filter is not saturated, the humidity being generally in the neighbourhood of 70 per cent to 80 per cent. After passing the air filter the humidity is increased to from 90 to 94 per cent, which means that the air in passing through the filter absorbs moisture. The temperature of the remaining water in the filter is reduced by the partial evaporation, and, as the unevaporated water is recirculated, its temperature would continue to diminish and is only prevented from doing so by the heat abstracted from the incoming streams of fresh air. For given conditions, a state of equilibrium is soon reached. This was demonstrated repeatedly on tests carried out over a period of three or four years on filters situated in different parts of the country. In the example mentioned, the air was drawn from outside the engine room.

With regard to high-voltage alternators, I am aware

of the 30 000-volt machines which are in operation in Italy, but I understand that some difficulty has been experienced in their operation. High voltages have already received consideration in this country, and I think that if power engineers wish to have machines which generate direct at the higher voltages, and are prepared to submit their proposals and to accept some portion of the responsibility, manufacturers would be prepared to undertake construction in this direction, at any rate in the case of machines of the largest output.

I did not propose to deal in the paper with the question of earthing alternators. As Mr. Selvey states, this is a question for very lengthy treatment, but the example was given to illustrate the injurious effects of the harmonics in the wave-form setting up high-frequency currents through the star point.

With the scheme of ventilation as described in the paper, the air pressure has been reduced to 4 inches (water gauge), and this figure includes the drop in a normal length of duct and in the air cooler.

Mr. Selvey appears to be uncertain as to my conclusions on the breaking of the alternator main field. I should explain that it is proposed to operate the main field switch (without discharge resistance) in emergency only, that is, in case of a breakdown on the alternator or for any other similar reason. It is therefore opened only when the protective relays operate, and not when the main alternator switch is opened by hand. Manufacturers are now prepared to provide the protective apparatus to function in this manner. There is no necessity to open the main field switch during the normal operation of the plant, while the alternator is fully excited.

In reply to Mr. Partridge, the limit of pressure for alternators of which there is experience available in this country is 13 000 volts. Several machines have been in operation (some for over 12 years) with satisfactory results, so that with the 25 000 kVA machine at 3 000 r.p.m. there would be no difficulty in dealing with such voltages. The end caps for supporting the rotor end-windings are made of nickel chrome steel, which has been in use since 1912, and its qualities have been gradually improved. The percentage of nickel is 3½, and the percentage of chromium less than 1.

The sketch of the stator windings in Fig. 11 in the paper is simply a diagram for illustrating the type of joint; the packings for the support of the windings have been purposely left out for clearness. In the designs described, packings are provided in the windings, and supports are provided for the conductors where they leave the slots. Such windings have been subject to the most severe short-circuits and have withstood them without being disturbed.

The multiple joint avoids the use of several parallel paths through the alternator where a heavy current has to be carried. Where two joints are used on one core conductor to connect to the end connectors, it would probably be necessary on other types of windings to use four or more parallel paths completely insulated one from the other, with a correspondingly increased number of joints. The round strand is preferred as being the most suitable construction. With round wires the danger of the primary insulation on the individual wires being damaged is reduced to a minimum. With the use of rectangular strip in the laminated construction of conductor, there are inherent difficulties which have been dealt with in earlier papers.* Apart from the mechanical difficulties, the losses in such a design of conductor, due to the unequal distribution of current, are not eliminated. The completely stranded cable described in the paper provides the complete solution of this difficulty.

The windings with tunnel slots, in practice, have proved equally or more accessible than with open slots. In the design adopted with the tunnel construction, where a fault has occurred it has been found possible to replace the windings and repair the damaged core without disturbing the other parts of the stator. No difficulty has been experienced in getting rid of the air space round the conductors, and in preventing the brush discharge. This question has been given careful consideration, with most satisfactory results.

Mr. J. S. Highfield made reference to these difficulties in a short contribution to the *Electrician* † in 1905. The remedies which were then suggested have been found to be equally applicable to present-day machines. The sides of the slots are made as smooth as practicable and are coated with insulating varnish. Protection is given to the conductors, when being drawn into position, by special insulating liners. With the flexible insulation there are a few simple workshop precautions to be taken in the assembly of the conductors in the slots, but any one bar can be readily replaced without disturbing the remainder of the windings or the insulation. The flexible insulation, besides having advantages in other directions, allows for the necessary expansion and contraction, without danger of rupture. As regards through bolts for holding the stator core, experience has proved that tight cores can be built without them.

Mr. Partridge suggests that the stator should be split transversely, in order to shorten the length of core supported by such bolts. Presumably, there would still be only one rotor, otherwise it would be equivalent to putting two alternators in tandem. The idea naturally arises in the mind of designers when having to contend with difficulties of the long machine, but such complication has not up to the present proved necessary. Mr. Partridge raises objections to the use of the separately driven fan. This can be readily fitted to an extension of an auxiliary pump motor, an arrangement which would eliminate the necessity for an additional motor. Fig. D shows the fan fitted on an extension of the extraction pump motor shaft on a 12 500 kW set, running at 3 000 r.p.m. It will be seen that the lay-out is very simple. The speed of the fan, as a rule, does not exceed 750 r.p.m., and is lower on the larger machines. I have had very wide experience with the use of the separate fans, and no serious difficulties have arisen on any of the plants on which they have been installed. With the separate fan there is an improvement of 1 per cent in the efficiency of the alternator, over that of the alternator fitted with

* See, for instance, *Journal I.E.E.*, 1920, vol. 58, p. 128.
† *Electrician*, 1905, vol. 54, p. 573.

fans on the rotor. This figure allows for the power taken by the fan motor.

The difficulties of supporting the rotor end-windings, those due to expansion, and the danger of side slip, have all been investigated. Special packings of asbestos cloth and synthetic resin are now manufactured, which have proved satisfactory for the comparatively low voltages at which the rotors are operated.

Dr. Thornton's remarks are of interest. The tests on stability which I have given in the paper have extended over several years, but I have only recently been able to put together the results in a complete form. The use of a permanent resistance in the rotor circuit will increase the main field losses, so that it would have the same effect as the main field regulator, and is subject to the same objections.

I am pleased that Mr. Taylor agrees with me on the question of the running of the rotors at comparatively low peripheral speed, and that his designs have in some directions run parallel with my own. I notice that in Fig. C he has now adopted my suggestion to fit a second motor.

I agree with Mr. Shaw that great credit is due to both Mr. Bond and Mr. Thompson for the early work done on alternator air coolers. The cooler question was discussed with them, I believe, as early as 1912. So far as the use of inert gases in the closed circuit is concerned, I do not think this is necessary. It is a complication and I think that Mr. Shaw will agree, from his experience of station plant, that it would be somewhat of a nuisance.

I agree with Mr. Shepherd that every effort should be made to improve the mechanical construction of alternators. It is a natural desire on the part of designers that the mechanical construction of high-speed alternators should be improved. Present-day design has proved itself to be a robust construction, and Mr. Shepherd's doubts cast upon the design of conductor have not proved in practice to have any foundation, as the conductors after many years of operation have upon removal been found to be in an excellent state of preservation with the insulation undisturbed. The designs illustrated have withstood the most severe short-circuits, and have proved that both conductors and insulation will withstand " the tremendous hammer-like blows on short-circuits." I realize that the enclosing of the whole of the windings in metal, concrete or similar material, has great attractions, but again Mr. Shepherd must not forget that there are many difficulties which prevent this being done, amongst which the first that occurs to me being the expansion trouble. I do not think that we have been backward in considering the liquid cooling of alternators, as this problem has long been one of many subjects for research by manufacturers.

Mr. Taylor's and Mr. Hill's views upon the question of field-breaking on the whole confirm the conclusions in the paper, but the tests show that with the main field circuit opened suddenly by a simple (quick-break) switch, the alternator voltage falls more rapidly than under any other condition. The increase in the value of the alternator reactance due to the tunnel slot is actually greater than the estimate given by Mr. Hill.

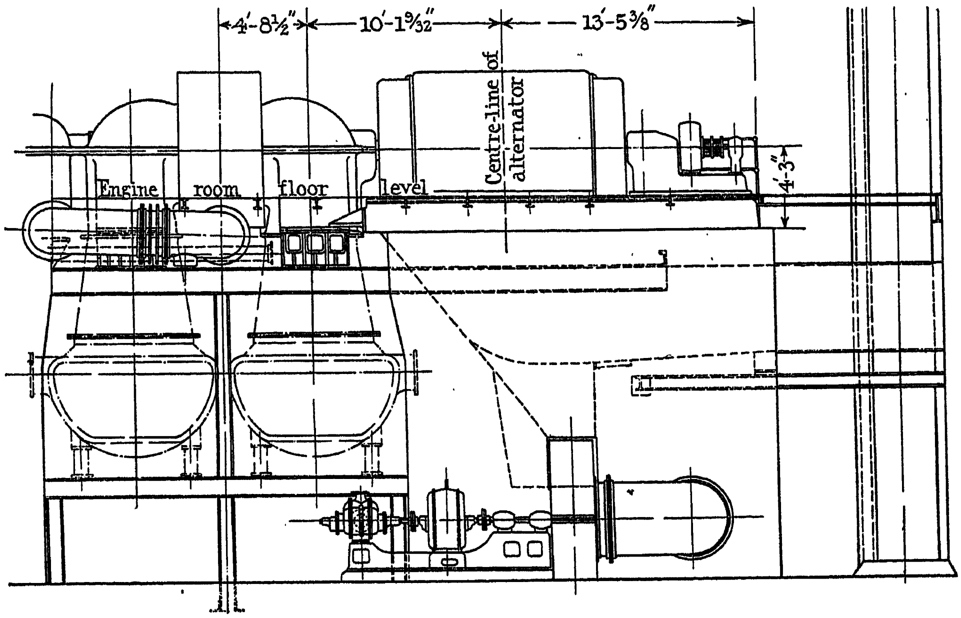


FIG. D.—12 500-kW turbo-alternator, showing ventilating fan coupled to extraction pump motor.

Scottish Centre, at Glasgow, 13 February, 1923.

Mr. C. W. Marshall: Some figures of alternator failures which have occurred in Glasgow may prove of interest. Out of a total of 21 turbo-alternators installed, 16, or 76 per cent, have failed. Considering machines of modern construction only, the failures allocated to the different firms which have supplied the machines are shown in the following table.

Firm	Capacity of sets, in kW	No. of sets	No. of failures	Percentage of failures
A	6 000	4	1	25
	18 750	3	3	100
B	6 000	2	1	50
	18 750	2	0	0
C	6 000	2	2	100
	3 000	1	1	100

Only serious failures are included in the table, and the figures appear to indicate that alternators are very unreliable, but this is, of course, not the case. The troubles which have occurred are due to the following causes: (1) Inability of windings to withstand short-circuits on the external system; (2) slack cores due to flimsy end plates; (3) defective arrangement of out-going leads between alternator and cable-sealing bells; (4) magnetic-circuit failures; and (5) rotor-winding failures. The last-named have all occurred in rotors of the laminated type, and have not been of a very serious nature. I shall be glad if the author will deal with the following questions in his reply. Are the percentages of breakdowns (Fig. 2) based on the total number of alternators installed since 1912? On page 442 the author emphasizes the necessity for examination and testing. What tests are recommended, and how often should they be applied? What increase in efficiency results from the use of tunnel slots? Referring to the integral and separately driven fans mentioned on page 448, can the author give the quantitative figures in regard to these two types? What are the relative costs of the ordinary wet air-filter and closed systems of ventilation? Is the quantity of oxygen in a closed system not sufficient to cause combustion of all the insulation in the machine in case of fire?

Mr. D. T. Powell: The author considers that it is advantageous to have a soft wrapping round stator bars instead of insulating them with a hard material, and I recently saw a case in which this preference seemed justified. Several large alternators were built for a 6 600 volt supply and the engineer considered that it might be an advantage to wind the machines for only about 2 500 volts and to put transformers in series with them. In practice this did not prove a good arrangement because the insulation of the stator bars broke down, the very contingency that he was trying to provide against. These stator bars were, of course, carrying a very heavy current, as the machines were of about 8 000 kW capacity, and naturally the copper expanded a great deal. The result was seen when some of the bars were taken out for examination. Not only bars which had broken down were removed, but also some which had not failed. At first sight there appeared to be no defect at all, but when the bar had been cut into sections one could see that the mica inside the outer covering was entirely pulverized, showing the extent of the relative movement between the hard mica tube and the copper. This continued in the machine until finally the insulation broke down at the corners of the mica tubes. There is, I think, no doubt why this insulation failed. The only remedy suggested at the time was to rewind the stator bars and apply harder insulation. I am unable to state whether these re-insulated bars have been more satisfactory. I think that a flexible wrapping would have been better and would have allowed the copper to expand without damaging the insulation. In that connection I would also suggest that the drying-out of alternators may do a considerable amount of harm, especially if carried out, as it is sometimes, with direct current. The current simply heats the winding without heating the core, and then relative movement between the copper and the insulation takes place and very probably causes permanent damage. Other people dry-out by short-circuiting an alternator and running it at something approaching full-load current. This is probably a better method but may also lead to trouble, as the excitation is very small and the heat is largely carried by the copper. In most cases it should be sufficient to run the machine unexcited for a good many hours and allow the windage to start the drying of the machine, and thereafter, if a reasonable insulation resistance be obtained, gradually to excite the machine, taking a considerable number of hours to bring it up to full voltage.

Mr. F. H. Whysall: My own experience bears out the evidence given in Fig. 2, which illustrates the very low percentage of failures of Parsons alternator stators in the British Isles during the past 10 years. It appears that all the failure percentages given are less than 1 per cent. In the list of Parsons alternators (Table 1) I note that the largest size actually installed for a speed of 3 000 r.p.m. is 18 750 kVA, and it is gratifying to note that, as the author points out on page 441, in this country we are ahead of America as regards size and speed rating, although quite recently an argument for using units of not more than 10 000 kW capacity was that this size represented the limit for a speed of 3 000 r.p.m. On page 439 the author very properly gives credit to de Laval for developing a satisfactory form of double helical reduction gearing for use with his simple impulse turbine, and I have seen early forms of this in collieries in South Yorkshire doing very heavy work through shafts no thicker than a lead pencil. While there appears to be no real difficulty about gearing in connection with turbine drives in practice, there is no doubt that much trouble has been experienced, in my opinion due more to inexperience or faulty workmanship of engineers responsible than to any other cause. There is no

doubt, however, that gearing is a complication which anyone would wish to avoid, if the object could be accomplished by other and better means. Reverting to the question of breakdowns in alternator stator windings, the author does not refer to the valuable help which manufacturers have received in the prevention of serious breakdowns by the use of extremely sensitive and efficient modern systems of protection. Many faults which under previous conditions might have resulted in complete burn-outs, are so quickly dealt with that no serious damage is done, and it is only in an exceptional case that a fault occurs of such a nature as to do serious damage. I am in agreement with the author's views in regard to ventilation. In the case of a continuous stream of fresh air it has been my experience that large quantities of dust accumulate in ventilating ducts, no matter what kind of filter is used. I have also heard of a case where with a wet air-filter the supply of air was completely cut off owing to low-temperature conditions which caused the filter to freeze up and shut off the air supply entirely. I am glad that the author holds the opinion that the introduction of a main-field regulator for exciters is not essential, because I think that no power station engineer was ever in favour of the complication. The author makes no reference to instability of excitation due to the low voltage of the exciter. I refer to the possibility of interruption owing to defective brush contact. I have known the mere contact of an attendant's oily finger on slip-rings or commutator to cause a serious interruption of the field circuit.

Mr. A. E. McColl: I am particularly interested in the latter portion of the paper in which the author gives the voltages in the rotor under short-circuit conditions. In 1910 similar trouble was experienced with an alternator in this district. Prof. Miles Walker's paper * on the short-circuiting of alternators pointed the way to a solution. The rotor end-caps when taken off showed signs of arcing and pitting on the portions adjacent to the core. I believe that the actual separation distance was about ½ mm. It was thought that the arcing was probably caused by current surges set up by large reciprocating-engine-driven alternators running in parallel with the turbo-alternator. Tests were made, but the results did not indicate that such was the case. Ultimately, however, the cause of the trouble was traced to external short-circuits to which the alternator had been subjected. The obvious solution, in view of Prof. Miles Walker's paper, was to bond the rotor end-shields rigidly to the core. The author strongly advocates the separately driven fan. With large turbo-alternator installations one is prepared to sacrifice efficiency to a small extent in order to obtain a reliable and secure drive for auxiliary plant. I think it preferable to have a direct-driven fan even at the sacrifice of ½ per cent in efficiency, merely in order to reduce the number of parts which may fail. It is most unsatisfactory to have a large unit temporarily out of commission due to the failure of some small auxiliary part. The author condemns dry-cloth filters and I am sure that we are all in agreement with him on this point. Applied to small machines they are not very satisfactory and in certain locations and under certain atmospheric conditions a cleaning staff in constant attendance is practically necessary. In large machines the dimensions of a dry-cloth filter are so considerable that the arrangement becomes impracticable. The author condemns wet filters on the score that free moisture is apparently carried through. The detection and measuring of this free moisture is not at all a simple matter and I should like the author to give some information on his method of research in this direction. Some time ago I had a number of tests made in order to arrive at a figure for the free moisture, the test procedure being to insert in the incoming air a search coil calibrated for percentage humidity against insulation resistance. If the insulation resistance for a corresponding percentage humidity in the incoming air fell below the calibrated curve, the assumption was made that free moisture was present. It was not possible to say, however, to what extent moisture in excess of natural humidity was present. The water cooling of rotors is advocated, but what is its advantage? Rotor excitation forms a very small proportion of the total loss and if there is any gain it appears to be in the quantity of air used. As this is only a matter of 7 to 8 per cent, the small gain obtained does not seem to justify the additional complications entailed in water cooling. It would be interesting if the author would give his opinion regarding the highest permissible voltage allowable for turbo-alternators. Mr. B. G. Lamme when discussing a paper before the American Institute of Electrical Engineers some time ago laid great stress on the fact that 11 000-volt alternators were successfully running with one phase earthed on single-phase railway service. This, he maintained, was equivalent to a 19 000-volt three-phase alternator running with its neutral point solidly earthed. If the generating pressure can be raised to 19 000 volts three-phase, as Mr. Lamme's statement seems to imply, the range of direct transmission can be increased without the use of transformers. Can the author say if such a proposition is feasible?

Mr. E. Seddon: The subject is of special interest to central station engineers, as well as to designers. High-speed alternators with rotors of small diameter entail longer cores and a correspondingly increased length of shaft between the alternator bearings. Such design calls for greater refinement in balancing the rotors dynamically. Up to the critical speed the rotor revolves about the centre of the shaft, and at higher speeds tends to revolve around its own centre of gravity. Information on methods of balancing is lacking. I have obtained good results by placing weights 120° behind the mid-point of the shaft markings. I should like the author to express his views on this point. Until some genius evolves a design for moving a balance weight in the rotor whilst running at high speed the balancing of these machines will remain a laborious operation. The author refers to the overheating of end caps. I have had experience of this trouble where the insulation below the caps was almost totally destroyed, and it was found that the only remedy was to make the caps a thoroughly good fit on the rotor core. I disagree entirely with the author in regard to the question of separately driven fans for supplying cooling

* *Journal I.E.E.*, 1910, vol. 45, p. 295.

air to the alternators. In my opinion we have far too many accessories attached to these large units. It is a very serious matter for a large machine to be put out of service owing to the failure of the fan motor or its wiring. I know of two cases where a turbo set had to be shut down owing to the failure of the fan motor. I think that most central station engineers will agree that it is preferable to make each unit as completely self-contained as possible. The author's explanation of reverse polarity on exciters, and the method proposed for overcoming this difficulty, are of great interest.

Mr. M. Pitt: In order to reduce excessive eddy-current losses in stator slot conductors the author advocates the use of a special standard conductor. While this may occasionally seem necessary, my experience shows that machines likely to be subjected to heavy short-circuits require windings to be as strong as possible. In any but small machines the stator winding can usually be arranged to have 1, 2 or 4 bars per slot, and it is quite possible to design a suitable solid or composite slot conductor in which the eddy-current losses are comparatively low, even on low-voltage machines where the stator current is heavy. It would have added to the value of the paper if the author had given some particulars of his experience with modern fireproof insulated rotors. On large machines the problem of providing even cooling and eliminating hot spots is a difficult one. The stator is less difficult to ventilate than the rotor, especially as the dimensions are not so restricted, and if the stator be cooled properly the cooling of a fireproof rotor is not of special consequence. The limiting factor to the output of large 2-pole machines is then likely to be the magnetic loading—probably the saturation of the rotor core. Mr. Marshall asked for definite figures regarding separate ventilating fans. On a 5 000 kW 3 000 r.p.m. turbo-alternator the friction, windage and fan losses are approximately 100 kW. The actual rotor windage and friction losses are only a small proportion of this, so that if the external fan is considered desirable—and it might be coupled to one of the motor-driven auxiliaries—there is a possible saving of 40 kW, as the efficiency of a high-speed rotor fan is seldom higher than 25 per cent. Eddy currents in the rotor and arcing to the end bells are likely to occur unless special care is taken in fitting the caps and keys to ensure a good metallic contact. The author gives an instance of excessive rotor heating caused by flux pulsations as the result of bad tooth spacing. Load flux waves, especially with good power factors, are distorted and vary considerably. A steady stator M.M.F. wave-form would reduce flux variation and also the rotor heating. Has the author ever experimented with chorded windings, with a view to eliminating the wide variations of the resultant stator M.M.F. wave?

Mr. A. P. Robertson: Regarding the air-cooling system, I think that we shall ultimately adopt a closed type. There is a definite amount of oxygen in the air, and in the closed circuit there may not be enough oxygen to burn even the insulation, but if the insulation were burned the copper and other metal parts might be saved. When a burn-out takes place in an alternator, the fanning action of the rotor is similar to that of the fan in a smith's fire, and the rush of oxygen burns up the metal. I am not sure what effect the rush of inert gas would have on the metal, but I should imagine that it would not be so serious as oxygen. I have had some experience of exciter instability. In the ordinary shunt-wound exciter the time-lag between the movement of the rheostat handle and the building up of the voltage is quite appreciable. On page 453 the author mentions that the voltage on the exciter has been built up by means of the rheostat preparatory to synchronizing. Owing to the time-lag the voltage is still building up, and resistance has then to be inserted for the purpose of steadying the voltage. It is very difficult at this juncture to keep the voltage constant. In order to overcome this difficulty it has been a common practice to energize the exciter field by means of a battery. The exciter voltage then responds very quickly to any movement of the rheostat and no trouble has been found due to the variation in voltage of the battery when charging. We have used this method for many years in Glasgow and are still doing so, but there is no doubt that it would be an advantage if an exciter could be produced which would be stable and would also respond quickly to any movement of the rheostat. This would be very much better than having resistance in the main field circuit, and would also eliminate the battery, which is undoubtedly a weak link in the chain.

Professor G. W. O. Howe: With reference to the curves shown in Fig. 1, I should like to know why, in plotting the ordinates, the power of the machines has been multiplied by their speed. If the object is to represent the size of the machines, one would expect to find the quotient and not the product. The author has shown oscillograph records of the wave-form of the voltage. I presume that tests were made to ensure that the damping of the oscillograph was correct. It would be interesting to learn whether any attempt was made to detect the presence of the tooth ripple by methods of resonance. Although one feels a certain amount of pride in the success of British electrical engineering firms in making such very large alternators, I do not know whether the policy of installing a small number of these very large units, instead of a large number of small units, is a wise one. I am afraid that those in charge of power stations are rather tempted to emulate one another in putting into their stations a few of these huge machines, thus greatly reducing the real factor of safety of the station. I have grave doubts as to whether the gain in efficiency, in cost or in space, obtained by installing, say, 4 or 5 huge alternators instead of a dozen or more generators of one-half or one-third the size, is sufficient to justify the increased risk of a serious breakdown imperilling the continuity of supply, especially where the whole industrial activity of a large district is dependent upon the electrical supply.

Mr. W. Ross: In describing the patented method of cooling an alternator, the author recommends a separate fan for supplying the cooling air, basing his recommendation on the score of economy. To my mind the use of a separate fan is a retrograde step, as it only secures increased economy at the expense of reliability, and in any case the increase in economy

must be very small. The majority of engineers will, I think, agree that a self-contained machine of average efficiency is to be preferred. I am interested in the author's description of the closed system of cooling, and should like to have his opinion regarding the use of spray coolers in place of surface coolers, which seem to have some favour in America. The connection of the cooler to the suction side of the pump seems rather dangerous, as, in the event of a tube splitting, the pump might lose the water and serious damage result before this was noticed. The reduction of fire risk seems to me to be very clear, as in addition to the restricted amount of air there are also the products of combustion to dilute the already small quantity of oxygen present. It was stated recently in an American paper, as the result of some tests with CO_2 for fire extinction, that air diluted with 10 per cent of CO_2 would not support combustion. I should also like to know the author's opinion with regard to the best methods of extinguishing alternator fires.

Mr. J. Rosen (*in reply*): The information given by Mr. Marshall, based upon his experience of alternator breakdowns, is instructive. In Fig. 2 the percentage of breakdowns is based on the total number of rotating-field alternators installed and includes breakdowns on all the early machines as well as the more modern ones. In reply to Mr. Marshall's question on the tests to be applied in the periodic examination of the plant, I would suggest the following:—

Preliminary.—(1) After the plant has been in commission for about two months, the alternator stator end shields should be removed and the stator end windings examined for possible movement due to short-circuits. The winding stud nuts should be tightened. (2) After the first heavy short-circuit on the alternator the stator windings should be examined at the first opportunity.

General.—(1) The alternator should be opened out once every 12 months and the stator end shields and rotor removed. The stator core, conductors, and end windings should be examined thoroughly for movement and abrasion of the insulation. The winding stud nuts should be tightened, if necessary. (2) The complete stator windings should be pressure-tested to 50 per cent above working pressure, between phases and to earth for one minute; the stator windings during this test should be dry. Such an examination should be carried out at the same time as the annual overhaul of the turbine is made.

It is difficult to give the exact improvement in efficiency resulting from the use of the tunnel slot, but this improvement is quite appreciable, as not only is the flux in the air-gap and stator teeth more uniformly distributed, but the pole-face losses are reduced to a minimum. It has, however, been possible to obtain exact figures for the improvement in efficiency when using a separately driven fan. For example, a 5 000 kW alternator requiring 20 000 cub. ft. of air per minute for its ventilation would, if ventilated by fans on the rotor, absorb 90 kW, or 1·8 per cent of the output. From this figure would be deducted 10 kW for the loss due to the windage of the rotor body, leaving 80 kW as the actual loss in the fan. This is a conservative figure and compares with the power of 20 kW absorbed by a motor driving a separate fan. The actual gain by using a motor-driven fan is therefore 1 per cent of the output. This gain remains approximately constant for turbo-alternators up to the largest sizes.

Concerning the relative costs of the wet air-filter and the closed system of ventilation, the air coolers are little or no more expensive than a good design of wet-air filter. The enclosed system of ventilation has the further advantage that there are no long external ducts, so that the total cost in most installations would probably be less than when using the ordinary wet air-filter. The volume of air in the enclosed circuit of a 10 000 kVA alternator is approximately 1 100 cub. ft., containing 20 lb. of oxygen. This quantity of oxygen could consume $7\frac{1}{2}$ lb. of carbon or about 20 lb. of wood, but as the principal product of combustion is carbonic acid gas, and a flame is extinguished when only 4 per cent of carbonic acid gas is present, the amount of wood consumed would only be about 1 lb. The total weight of combustible material in the alternator, including wood packing and insulation, exceeds 400 lb.

Mr. Powell agrees that the flexible insulation is the most satisfactory solution of the stator insulation difficulties. I am aware of the machines to which he refers, and it will probably interest him to know that one of these alternators has been replaced by a Parsons alternator, with the flexible insulation which is now running direct on the 6 600-volt supply in parallel with the existing alternators, coupled through the transformers. It has now been running for two years without difficulties of any kind.

I agree that unless precautions are taken in drying-out alternators under short-circuits, local heating must take place. In my opinion, the best way to dry an alternator on site is to run it below half speed, and to pass the necessary current through the stator windings under short-circuit. By this means, dangerous local heating due to the eddy currents induced under the conditions occurring when the alternator is run short-circuited at full speed is eliminated.

Mr. Whysall refers to difficulties with gearing, and I can assure him that Messrs. Parsons have had no failures of gearing which has been fitted in land installations. I agree that the present forms of alternator protection are a great safeguard and in many cases have prevented a complete burn-out by tripping the machine from the busbars.

I would refer Mr. McColl and Mr. Ross to my reply to Mr. Partridge (see page 466) on the question of alternator ventilation. I would also refer to the reply to Mr. Marshall, from which it will be seen that the improvement in efficiency by using a motor-driven fan is 1 per cent.

In the original tests for free moisture, when air filters were used, air was tapped off and the moisture contents measured by means of the ordinary calcium chloride tubes, but later, in order to obtain a more practical method, moisture detectors were designed, and it is now possible to obtain a check upon the free moisture present in the cooling air, without providing elaborate apparatus. The moisture detector as originally

designed consisted of a brass or copper cylinder, around which a sheet of press-spahn 0·2 mm thick was bound with Eureka wire spaced well apart. The insulation resistance of the press-spahn between the Eureka wire and the tube was measured by means of the ordinary testing instruments, such as a "megger." In using this apparatus two similar detectors are employed, one of which is screened by means of a blanket to prevent

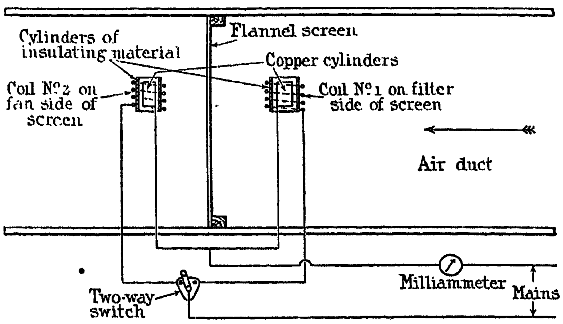


FIG. E.—Diagram of connections for moisture-detecting apparatus.

any free moisture present from impinging on it, and the second one is exposed directly to the cooling air. By taking a series of readings, a direct indication of the condition of the air leaving the filter is obtained. The arrangement is shown diagrammatically in Fig. E and the curves are shown in Figs. F and G with short explanatory notes. Fig. E also gives a diagram of connections for measuring the condition of the insulation by means of a milliammeter, the detector being coupled to the d.c. supply.

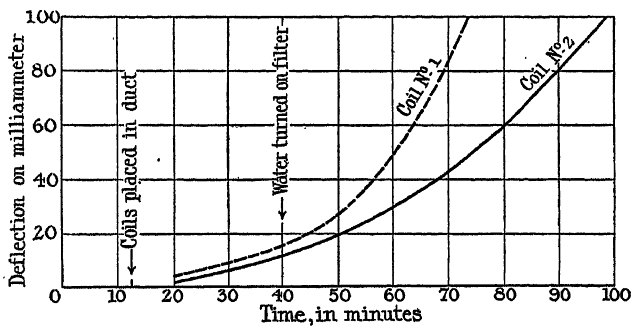


FIG. F.—Moisture-detecting apparatus. Curves showing relation between insulation resistance of two coils.

The insulation resistance of each coil falls at the same rate until the water is turned on the filter, after which the insulation resistance of the coil on the filter side of the screen falls more rapidly. This is due to the presence of free moisture in the duct, which only affects this coil.

I would refer Mr. McColl, on the question of high voltage, to my reply to Mr. Selvey in the London discussion. There are difficulties to be surmounted, but I see no reason why, if engineers desire them, three-phase alternators should not eventually be designed for generating direct at 20 000 volts.

In reply to Mr. Seddon, there are naturally many difficulties in balancing electrical rotors, but I think that the most suitable method is to run the rotors up to speed to enable the windings to take their final positions. I prefer that the rotors should be run up to overspeed while the windings are hot. On the question of separately driven fans, I would refer Mr. Seddon to my replies to previous speakers.

In reply to Mr. Pitt, the modern rotors insulated with the special insulation to withstand high temperatures have proved satisfactory after many years of operation, and no troubles have been experienced due to the qualities of the insulation used. The question of types of stator windings is one for very wide discussion and cannot be dealt with in detail here. Although chorded windings are used, the wave-forms given in the paper were obtained without their use.

In reply to Mr. Robertson, I have had experience of only one fault on an alternator fitted with the enclosed-circuit system of ventilation, and in this case the machine was tripped from the busbars by the operation of the self-balanced protective relays; one conductor only was damaged and the remainder of the windings and insulation were untouched. The balanced protective gear localized the fault and I think the enclosed system of ventilation was instrumental in preventing

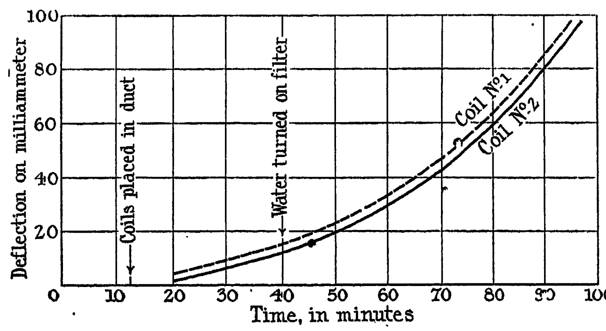


FIG. G.—Moisture-detecting apparatus. Curves showing relation between insulation resistance of two coils.

The insulation resistance of each coil is falling at the same rate, clearly indicating that no free moisture is passing into the air duct.

the burning of the adjacent insulation, owing to the limited quantity of air available for combustion. This question is dealt with fully in my reply to Mr. Marshall. The separate excitation of exciters is not now necessary, as with the use of the series turns on the exciter poles the exciters can be made stable at all voltages required for the operation of the plant.

In reply to Professor Howe, the product of the power of the machines and the speeds has been used in Fig. 1 as it gives a "Factor of Difficulty" in designing and manufacturing such plant. That the wave-forms of E.M.F. of the alternators described in the paper are satisfactory, is confirmed by the fact that in no case has there been disturbance in telephone systems where such alternators are used. It may sometimes be felt that the size of alternators is increasing too rapidly, but it must be remembered that the size of plant is only comparative, that the earlier and smaller machines were designed for the loads then available in one station and that the large units now being considered are very necessary, in order to deal with the very much greater demands for power. Remembering that power stations are now interlinked, there is more available spare plant than in the earlier days; the number of failures of

supply due to turbo-alternator breakdowns may be considered negligible.

In reply to Mr. Ross, the only spray-type cooler which I saw in America used for the enclosed system of ventilation had been discarded for the ordinary filtering system. The objections to such coolers are the same as when they are used in the normal way for filtering the air. If a fault is found in a tube of a surface cooler the section of the cooler should be put out of commission and the tube plugged immediately. The precaution of putting the cooler on the suction side of the pump is to prevent water from leaking into the air ducts through small holes only. Several methods have been described for extinguishing fires but I think that the enclosed system of ventilation is the greatest safeguard. I have had steam sprays fitted to alternators, but fortunately it has not been found necessary to use them. Chemical extinguishers should be avoided, as the chemicals harmfully affect the insulation and after their use it is advisable entirely to rewind the alternator. There is also the possibility of further breakdown due to the action of the chemicals upon the varnish.

North Midland Centre, at Leeds, 20 February, 1923.

Mr. J. W. J. Townley: I note that in Table 1 reference is made to a machine of 47 500 kVA; is that a single alternator or is the output obtained from two machines connected to the shafts of a cross-compound turbine? The latter arrangement is, I believe, preferred by the turbine designer for generating sets of that size. The author has dealt with high-speed turbo-alternators, but the turbine designer frequently desires to run his low-pressure end at a somewhat lower speed than the high-pressure turbine, which means two alternators in the case of very large sets, one running at the highest practicable speed and the other connected to the low-pressure turbine at a considerably lower speed. This, of course, greatly simplifies the problem for the alternator designer, and if Messrs. Parsons are now prepared to build single alternators of 47 500 kVA, the 100 000-kVA machine of the cross-compound design is within sight. With reference to these very large machines, some particulars were recently published of a 65 000-kVA turbo-alternator now being constructed in the United States. If the author has any information in regard to this machine (I understand that he has recently returned from America) I should be glad if he would give some details in his reply. The machine is, I believe, designed to run at 1 200 r.p.m. In a recent issue of a German technical journal some particulars were given of the 60 000-kVA turbo-alternators built in that country during the war, and certain particulars were also given of a design for a machine of 160 000 kVA running at 1 000 r.p.m. The rotor diameters were given as 2·25 m for the former, and 2·7 m for the latter. It appears that the peripheral speeds, and therefore the stresses on the rotors, of these and the American machine are very much in excess of anything hitherto contemplated in this country, and I should like to know the author's opinion of these proposals. Reference is made in the paper to the difficulties in obtaining satisfactory cooling in high-speed machines. When water cooling was proposed some years ago and actually carried into effect by Messrs. Parsons, I came to the conclusion that this system of cooling would be universally adopted for large high-speed machines, and I am now somewhat surprised to find the author of opinion that water cooling is unnecessary even for large machines running at 3 000 r.p.m. One can readily understand that in the case of a high-speed machine the relative proportions of iron and air space are considerably modified, the air space requiring a very much greater proportion of the whole, and this naturally results in a somewhat indifferent mechanical construction. The author points out that satisfactory core construction is important in the design of a reliable machine. Is the stator core construction in modern high-speed machines perfectly satisfactory when designed for air cooling? I am disappointed that no reference is made to the maximum temperatures reached in these machines, as I believe that manufacturers have a great deal of data, obtained by the generous use of embedded temperature detectors, as to the hot spots upon their machines, this information not being ordinarily passed on to the user. In an American journal recently some figures relating to the temperatures reached upon the Niagara Falls machines were given, and in one machine the maximum temperature was 390° F. in the stator copper, which appears to be excessive. I do not, of course, suggest that British machines ever reach such temperatures, but I believe that there are hot spots in many machines which reach temperatures very much in excess of anything which thermometers can indicate. I agree that rigid insulation should be avoided, as a certain amount of movement of the stator bars cannot be prevented, and for the effectiveness of the Parsons method of obtaining this flexibility I can vouch, as I have seen some insulation taken off a machine (after being in use for 6 or 7 years) which was then in a very soft flexible condition and would permit a considerable amount of movement of the stator bars without cracking. It may be that with the increasing length of modern alternators the operating engineer should consider more carefully the question of loading his machines and, in order to avoid excessive movement of the stator bars, should load the machine up slowly so that the copper and iron will heat and therefore expand together. The net movement of the stator bars would then be merely the difference between the expansion of the two metals. The total movement, even in the first case, is small, being about $\frac{1}{8}$ in. for a stator length of about 8 ft. and 120 degrees F. rise, but it must have an effect upon the insulation if constantly repeated. The author refers to the closed-circuit air filter. I quite agree that this is the best method of dealing with the air-cleansing problem, and it has the additional advantage of mitigating fire risks. He suggests that it is inadvisable to allow water to come into contact with air, but in a design of closed air filter which I have

recently seen, the water trickles down a series of plates in the form of a film. The advantage of this type of air filter is that there is no risk from burst tubes, which might have a serious effect. Has the author considered the use of fireproof insulation for end windings? One of the greatest dangers in a modern alternator is a fault occurring at that point, which usually sets fire to, and results in the complete destruction of, the windings. A completely fireproof construction would almost entirely remove this risk. The most valuable part of the paper is, I think, that in which the author gives particulars of his experiments with rotor caps. I feel that we are on the wrong lines in having solid metal caps, as the stresses upon the cylindrical cap are very unequal and tend to distortion. The old system of steel-wire or strip-bands was no doubt unsatisfactory, but this form of construction might be developed and be a more satisfactory solution of the problem than the present solid cap. The author refers to the rather high voltages which can be induced in the shaft and rotor body of high-speed machines. I have experienced this trouble. In order to prevent the circulation of current in the shaft some manufacturers insulate one of the bearing pedestals, but I think it is preferable to short-circuit the shaft inside the alternator bearings. The latter device, of course, involves brushes running upon the shaft at this point. On page 458 the author calls attention to the dangers of open-circuiting the rotor winding with a quick-break switch without discharge resistance, owing to the excessive currents which may flow through the keys, shaft and rotor caps. In a recent paper * it was suggested that to open-circuit these windings by means of a field switch without discharge resistance was a perfectly safe proceeding from the point of view of voltage-rise in the rotor winding itself; but the present author shows that there is another danger which must be borne in mind.

Mr. G. B. Melton: From a constructional point of view I am very much interested in the sand-blast action on the conductors. If by digging a hole in the ground near the point of air supply to an alternator it be possible to provide material which will strip the insulation in one minute, I think that we shall have to get rid of both dry and wet air-filters. I am also interested in the pressure set up in the water-cooled rotors. Perhaps the author will state the internal water pressure corresponding to a speed of 300 to 400 ft. per sec. The rotor bonding mentioned is a very satisfactory feature. Reversal of exciter polarity under short-circuit and other abnormal conditions does occur, but I have never found it to be very harmful. The instruments simply work off the scale and their connections have to be reversed. Two machines of which I have intimate knowledge used to reverse at very frequent intervals and no harm was done. The rotor end bells might be constructed similarly to a wire-wound gun, i.e. wound with rectangular-section wire, provided that the ends can be secured. I was rather surprised at the low voltage found by the author in the rotor body under short-circuit, and I should be glad to know whether it was a single-phase or three-phase short-circuit. Instances are known of the breaking down of the insulation under the exciter bearing, and on at least one occasion a machine was actually shut down because an arc was formed between an oil vent pipe and the stator, under single-phase short-circuit conditions. I believe that the existing practice in many American stations, particularly on the Canadian side, is to connect lightning arresters to earth across the rotor and across the exciter bearing pedestal in order to protect the insulation, and I should be glad if the author would deal with this point in his reply.

Mr. J. F. Mather: I agree with one or two of the previous speakers that the enclosed system of ventilation for alternators is now obtaining recognition, and that most large machines in the future will be designed with ventilating systems of this type. I also think that the Parsons design of ventilating system is the most scientific and most efficient in use at the present day, but the externally driven fan used is a weak link in the chain. The fan is such a vital piece of the apparatus that a failure of the air supply leads in a very short time to difficulties. I believe that with the Parsons machine, even if running on no load, a failure of the air supply will very soon result in a dangerous rise in the temperature of the rotor and stator if the field magnets are excited. This being so, I should like to suggest to the author a compromise between the inefficient fan mounted direct on the rotor shaft and the fan driven by a separate motor, the idea being to drive the fan by means of worm gears and shafting from the main shaft of the alternator in a similar manner to that in which the governor is driven at the steam end of the machine. There might be some little difficulty in arranging the shafting for the fan, and there would be a fairly considerable amount of power to be transmitted. In the case of a 15 000 KW set, for example, the ventilating fan absorbs about 170 h.p. I think, however, that the scheme would not present any insuperable difficulty, and it would certainly have much to recommend it from the point of view of reliability. It will probably be mentioned that such a design would entail an increase in the length of the machine, and with Parsons machines this is a very important point. A comparison between Parsons machines and those of equal output of other types will show that the former are usually somewhat the longer. From the point of view of calculation of steam consumption of the set this method of driving the fan would not be under any disadvantage, because it is usually specified that in calculating the consumption the power delivered from the alternator terminals shall be reduced by the power required for ventilating the stator and the exciter of the machine.* The question of reactance is also distantly connected with the ventilation of the machine. At first sight there may not appear to be any connection between these two things, but I speak now from the point of view of the general lay-out of the plant. When external reactances are to be used, a very convenient place for housing them is the space in the foundations directly beneath the

* J. A. KUYSER: "Protective Apparatus for Turbo-Generators." *Journal I.E.E.*, 1922, vol. 60, p. 761.

* With the gear-driven fan this power would be deducted automatically.

alternator. With the enclosed system of ventilation this space will be required for the air ducts and cooler, and the reactances will necessarily be placed elsewhere. The problem with which central station engineers are faced to-day is very often to fit a comparatively large-sized machine into an engine room that is very much too small for it, an engine room that was perhaps designed many years ago for plant of an entirely different type. It is not therefore always an easy matter to find a place for the reactances and at the same time to make a suitable arrangement of the main cables. From this point of view it appears to be desirable that all the reactance should be contained in the machine itself. I believe that external reactances when installed provide about 30 or 40 per cent of the total reactance in circuit. With the tunnel type of slot which the author recommends for other reasons, it should not be very difficult to include in the machine windings as much reactance as required.

Mr. S. D. Jones: Would it not be possible to design an air cooler similar in nature to an evaporative condenser? The air would be circulated through the cooler tubes and the circulating water would drip over the outside of these tubes. A steady stream of air could be directed against the water to carry off the vapour through air ducts to the outside of the building. This would involve an additional fan for the outside air circulation, and possibly the cooler to do the work would take up too much space. The cooler tubes would always remain clean inside, as only clean air circulates in them, and they could be designed to give the greatest possible cooling surface between the inside air and the trickling water outside.

Mr. S. E. Fedden: The author's remarks regarding the advantages of the Parsons stator winding are justified in practice, and the possibility of withdrawing a faulty bar with little or no disturbance to its neighbours is fully appreciated by those in charge of the operation of turbo-alternator plant. Our experiences with wet-air filters as applied to high-tension alternators confirm from many points of view the great desirability of the closed air system. Water-cooled rotors constitute a doubtful expedient, as apart from danger of possible leaks on to the E.H.T. stator winding there is danger of the circulation stopping without warning owing to the passages becoming choked. The author directs attention to the danger of breaking down field windings through the too rapid interruption of current. As "kicking" coils are now out of date and as the old and well-tried shunt break is not the latest practice, what is to be done? Perhaps a liquid starter converted to act as an "interrupter" might meet the case. With reference to the loss of field of shunt exciters on light load, as we were amongst the first to recommend the trial of a few turns of series winding on the Parsons exciters we can confirm this as a remedy. The design and general insulation of rotor slip-rings are not referred to; the steel rings should be not less than 2 in. broad, and a little more creeping surface should be allowed on the mica forming the foundation. The connection from rotor winding to slip-ring is often a source of trouble. The Parsons design has proved very successful owing to the attention given to these details. The author does not direct attention to the importance of main-terminal design on alternators. Possibly Messrs. Parsons have not experienced trouble in this respect. Their terminal connectors consist of broad laminated copper strip flexibly insulated and yet rigidly clamped between broad slabs of insulating material carried by gunmetal brackets. There being no porcelains to be broken by main cable movement, this terminal has proved most successful.

Mr. D. M. Buist: On the whole I agree with the author's remarks upon the subject of insulation, but as an additional security from the user's point of view I would stipulate that all coils on both stator and rotor, and especially the end turns, after being wound should be subjected to a temperature and pressure greater than will probably be encountered in operation. I am glad to note that the author's firm seems to have paid particular attention to the question of cooling the end turns, as this is practically the only portion of the windings where the cool air can be brought into direct contact with the source of the heat. Referring to the question of eddy currents in rotors, I am glad to see that the author devotes to it the attention that it deserves. I have encountered at least two breakdowns which could only be attributed to the eddy currents induced in the rotor caps. The first of these substantiates the author's opinion that to insulate the cap from the rotor is not a satisfactory remedy. This was the method adopted in the case to which I refer, and distortion of the cap, combined with mechanical weakness of the insulation, resulted in heavy sparking between the cap and the body each time the rotor circuit was opened. The second breakdown occurred on a larger machine of different make, and in this instance a piece of the cap weighing nearly ¾ lb. broke off and tore up the stator windings. When this happened the machine was on low load, and so in this case it is probable that centrifugal force completed what the sparking had commenced. In view of the above, therefore, I heartily endorse the author's recommendation that quick-break switches without discharge resistances should be employed to break the main-field circuit only in an emergency.

Mr. G. P. Henzell: I should like to make a few remarks with reference to ventilation. Most of us will agree that both the wet and dry types of air filter are, generally speaking, unsatisfactory in practice. I think that the closed system of ventilation is undoubtedly the right thing. I recently saw an alternator having a capacity of, I think, 10 000 kW, that had just been opened out after 12 months' running on the closed ventilating system; there was not even a speck of dust to be seen on the windings. I am not at all in favour of the separate fan, however, as it is an additional auxiliary. The author is probably correct in saying that we cannot design such an efficient fan to run on the rotor shaft, but I think that we can design a fan sufficiently strong mechanically. Even though it is less efficient, I think it is better than the separate fan with all the attendant risks of breakdown. I have never been able to get to the bottom of the question of alternator temperatures, as no one seems to have definite views as to what the limit is. The majority of operating engineers are strongly inclined to keep on the safe side. Personally, I think that the factor determining

the safe limit is, to a great extent, expansion, and not the temperature that the insulating material will withstand. I have had breakdowns on alternators, and in most cases examination showed that the conductors had moved inside the insulation, which then flaked or powdered off. I should like to endorse the remarks of a previous speaker on fireproof end-winding. I think this is a most important point; most serious damage is caused by end-winding fires.

Mr. J. Rosen (*in reply*): In reply to Mr. Townley, 47 500 kVA is the output of one alternator of the 50 000 kW unit, which has a total kVA capacity of 64 500. This unit is now being manufactured by Messrs. Parsons for the Crawford Avenue station of the Commonwealth Edison Company, Chicago. Where the load is available, it is not unreasonable to use 100 00-kW units with cross-compound turbines, and I am confident that such units will be installed during the next few years. The 47 500 kVA alternator mentioned above will run at 1 800 r.p.m. Mr. Townley asks if the figure of 2·7 m at 1 000 r.p.m. is safe. I think that this peripheral speed of 464 ft. per sec. is the maximum at which rotors should be run with the information at present

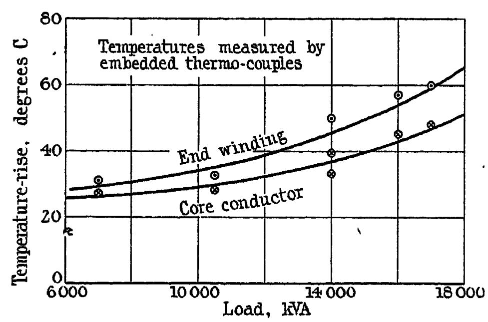


FIG. H.—Curves showing temperature-rise of end-windings and core conductors in an 18 000-kVA alternator.

available. Personally, I prefer not to exceed a peripheral speed of 400 ft. per sec.

In reply to Mr. Townley and Mr. Melton, research in the direction of steel-wire and steel-strip bands for supporting the rotor end-windings has been carried out, but a metal cylinder of some form must be used on which to bind the wire; otherwise, the wire has to be applied directly to the rotor windings. Alternator rotors have been fitted with caps filled with binding wire, owing to the difficulty in obtaining suitable high-tensile bronze, and have run quite satisfactorily. With the lower peripheral speeds, however, the complication of binding wire is not necessary. There are difficulties which prevent stators being entirely water cooled; and I have dealt with this question in reply to Mr. Shepherd (see page 467). The stator core in the present methods of construction and supports has proved to be very reliable.

I agree with Mr. Townley's figures on the movement between stator conductors and the core, but the flexible insulation has overcome these troubles. On the whole, I think that we do not run to such high temperatures in this country as in the plants manufactured in America. I attach a typical curve (Fig. H) of conductor temperatures in an 18 000 kVA alternator, as measured by embedded thermo-couples. With present materials it is impracticable to obtain a completely fireproof construction of stator winding, but with the enclosed system of ventilation the damage has been limited to the point of breakdown only; it has been proved that the damage does not extend to other parts, owing to the comparatively small quantity of air present. I find that the insulated pedestal is more satisfactory than the use of short-circuiting brushes.

I have had some experience of the coolers with water trickling down the plates, but this arrangement is similar to the eliminators in the ordinary wet air-filter; the water appears to collect at the edge of the plates and is blown over in the form of large drops.

In reply to Mr. Melton, the pressure in the tubes exerted by the water at 300 ft. per sec. is about $2\frac{3}{4}$ tons per sq. in. In regard to the voltage induced in the rotor shaft, this was under a three-phase short-circuit. I would remind Mr. Melton that even this pressure of 30 volts would circulate a very heavy current of some thousands of amperes through the rotor body. I have heard of the practice of connecting lightning arresters between one of the rotor terminals and earth, but I did not see in America an installation to which such a device was fitted. Although in this country their use was considered some years ago, I do not think that they have been adopted.

Mr. Mather proposes to use a fan geared in some way to the alternator shaft. I would refer him and also Mr. Henzell to Fig. D on page 467, in which is shown an arrangement used on a 10 000 kW machine for driving the fan from a pump motor. The greater number of Parson alternators are run without external reactances, but if reactances are proposed I have no doubt at all that provision could be made to incorporate them in the foundation lay-out with the enclosed system of ventilation. Naturally, their position must be considered before the foundation plans are settled.

It has been found that sufficient cooling surface can only be obtained by the use of "gilled" tubes, and that the rate of heat transmission from the air to the water is low and is the limiting factor in the design. The evaporative principle offers no advantage in this respect, and in addition entails, as pointed out by Mr. Jones, an additional fan and ducts. There is, therefore, not sufficient to be gained by the use of the evaporative principle to offset the additional cost.

I am very pleased to hear that Mr. Fedden's views coincide on the whole with my own. I do not think that in the normal operation of the plant it is necessary to utilize the special liquid "interrupter," as it is only necessary to open the main field in emergency or when the alternator excitation has been reduced; this can then be done by means of the ordinary quick-break switch.

Mr. Buist is correct in assuming that both the stator and rotor windings should be subjected to pressures greater than that which would be encountered in operation.

I agree with Mr. Henzell as to the difficulties due to expansion and to movement of the conductors. The helically stranded conductors with flexible insulation illustrated in Fig. 8 have replaced conductors of several alternators in which the laminated conductors with hard insulation were previously used.

THE USE OF SINGLE-CORE SHEATHED CABLES FOR ALTERNATING CURRENTS.*

By Professor W. CRAMP, D.Sc., Member, and NORA I. CALDERWOOD, M.A., B.Sc.

(*Paper first received 2nd September*, 1922, *and in final form 8th January*, 1923.)

SUMMARY.

It is frequently a matter of convenience to use single-core lead-covered cables for transmitting power by means of alternating current, and in such cases the magnitude of the loss arising from the eddy currents induced in the lead sheath becomes a matter of importance. Recently some power-supply authorities have refused to connect to their lines any distributing system depending upon the use of such cables.

The eddy losses in the sheaths of these cables may be divided into two groups, called herein "sheath eddies," and "sheath circuit eddies." The latter occur only when one or more cables have their sheaths connected at more than one place.

The losses are analysed for a single cable, a pair of single-phase cables, and a set of three-phase cables.

It is shown that the sheath eddies are in all cases negligible, and that the sheath circuit eddies may be kept within reasonable limits by proper regulations regarding the spacing of the cables.

It is suggested that the I.E.E. Wiring Rules should contain such regulations, and that so long as these are adhered to there is no justification for refusing to connect single-core lead-covered cables to any ordinary a.c. system. The necessary data are given for the framing of the regulations.

Similar questions arise regarding armoured cables. The results in this case are awaiting the conclusion of the experiments now being carried on at the University of Birmingham.

The adoption of alternating currents for small and large distributing systems has resulted in an ever-increasing use of cables provided with a protecting metal sheath, from which it follows that the effect of eddy currents in the sheath is of importance, especially in Great Britain, where underground lines are more common than in America or on the Continent.

The subject is also a matter of moment in many large works and collieries, especially in those cases where a change has been made from an old d.c. supply to a new a.c. system, in which it is desired to use as many of the existing cables as possible.

Again, paper-insulated cables admit of large currents for a given section of copper and a given temperature-rise, and the use of paper entails the use of a protecting waterproof sheath which is usually made of lead.

It is not always convenient to adopt a multi-core cable for an a.c. system. There are many instances where, on account of special circumstances, such as the run to be negotiated or the presence of existing cables, it is economical or convenient to adopt cables of the single-core type. In the course of practice extending over many years, one of the authors has never hesitated to use long lengths of single-core lead-covered cable on a.c. circuits, and has never had the least trouble due to heating of the sheath. Notwithstanding this experience, it now appears that some power-supply authorities are objecting to single-core a.c. cables, and even refuse to connect them to their mains. The reason for this action apparently is that these authorities fear the heating effect of eddy currents in the sheath which are induced by the current in the core of the cable itself and by neighbouring circuits.

Current textbooks contain little but vague statements as to the magnitude of such heating effects, though several recent American papers deal with other aspects of the problem. It therefore seemed desirable to calculate and put on record the relative magnitude of this loss as compared with that due to the normal resistance of the core itself. The justification for this comparison lies in the fact that the heat due to the copper core as well as that due to the eddy currents in the sheath must ultimately be dissipated by the surface of the sheath. If then we express both in the form of watts/cm^2 of the sheath surface we shall have a measure of the increased temperature-rise of the cable due to the sheath eddy currents.

The eddy currents in the sheaths of a pair of cables laid side by side, each carrying a known alternating current, may be divided into two main groups :—

(A) Eddy currents whose outward and return paths lie entirely in the sheath of one cable, called hereinafter "sheath eddies."

(B) Eddy currents whose outward path is along one cable, and return path along another, called hereinafter "sheath circuit eddies."

It will be manifest that the latter can never exist if each sheath is entirely insulated from every other, or if there is no metallic connection at more than one point of a pair of cable sheaths. Thus, if bonding, or switchgear wiped joints exist at only one end of a system, all currents of class (B) will disappear. But the currents of class (A) cannot be avoided altogether by any means short of a non-metallic sheath, which, if it could be devised, would eliminate not only these but many other troubles. We are of opinion that cable makers would do well to direct their attention to this suggestion, for so long as metal sheaths are used and wiring rules, particularly colliery wiring rules,

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

are what they are, bonding at both ends of a circuit is usually a matter of necessity.

If we can show that eddy currents of class (A) are negligible in magnitude, then power-supply authorities will be well advised not to irritate consumers by refusing to connect single-core cables to their systems, but to adopt such rules as will keep the heating losses due to (B) within safe limits.

To prove the former and to give data for the latter is our object in the following analysis, and we begin with currents of class (A). As a general case of common occurrence and one in which these eddy losses will be at their worst, we may consider a single-phase circuit consisting of a pair of lead-covered cables lying side by side along a straight run. We assume the mean radius of sheath to be r cm, the centres of the pair of cables to be l cm apart and the thickness of the sheath to be S cm. Since S is small compared with either r or l, the magnetic field at any point P in the sheath may be considered to be uniform throughout the thickness at that point. The distance l must always be greater than $2r$, so that the fraction $r/l = K$ cannot be greater than $0 \cdot 5$.

Referring to Fig. 1, and assuming that the cable

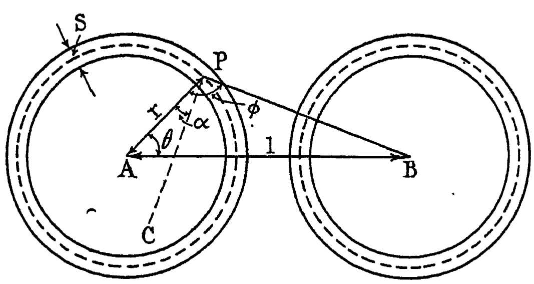


FIG. 1.

whose centre is at A carries a current $\hat{I} \sin 2\pi ft$ amperes away from the observer, for which the cable whose centre is at B forms the return circuit, then at the point P on the mean circumference of the lead sheath the magnetic field due to the current at A is always normal to the radius AP and clockwise in direction. Similarly, the magnetic field at P due to the current at B is always normal to BP and counter-clockwise in direction.

This second field may be resolved into two components, (1) along PA and (2) at right angles thereto. The circumferential field through P around A is therefore the sum of two components, while the field normal to the sheath is due to the current in B only. We thus have two series of eddy currents, the first due to the sum of the circumferential fields and tending to flow in radial planes, and the second due to the normal fields and tending to flow in tangential planes. If θ is the angle PAB, and α the angle APC (where PC is perpendicular to PB), the circumferential magnetic density at P is

$$B_1 = \frac{0 \cdot 2\hat{I} \sin 2\pi ft}{r}\left(1 - \frac{r^2 - rl\cos\theta}{r^2 + l^2 - 2rl\cos\theta}\right)$$

$$= \frac{0 \cdot 2\hat{I} \sin 2\pi ft}{r}\left(\frac{1 - K\cos\theta}{1 + K^2 - 2K\cos\theta}\right)$$

On the above assumptions, if the cable has a length L cm, then through a zone of the sheath of radial thickness y (from the mean circumference) and length L the magnetic flux is

$$\phi_1 = \frac{0 \cdot 2\hat{I} \sin 2\pi ft}{r}\left(\frac{1 - K\cos\theta}{1 + K^2 - 2K\cos\theta}\right)Ly$$

which will produce along an element of the boundary of the zone an E.M.F.

$$\delta E = -\frac{d\phi_1}{dt}$$

$$= \frac{-0 \cdot 4\pi f\hat{I} \cos 2\pi ft}{10^8 r}\left(\frac{1 - K\cos\theta}{1 + K^2 - 2K\cos\theta}\right)Ly \text{ volts}$$

Since the length of the cable is great compared with its circumference, the resistance of the element of the boundary is

$$R = \frac{\rho L}{rd\theta dy}$$

where ρ is the specific resistance of the material of the sheath.

The eddy current along the element is

$$di = -\frac{1}{R} \cdot \frac{d\phi_1}{dt} = -\frac{0 \cdot 4\pi f\hat{I}[\cos 2\pi ft](1 - K\cos\theta)}{10^8\rho(1 + K^2 - 2K\cos\theta)}yd\theta dy$$

The power lost in the element is

$$\delta Edi$$

$$= \frac{0 \cdot 16\pi^2 f^2 \hat{I}^2 \cos^2(2\pi ft)}{10^{16} r\rho} \cdot \frac{(1 - K\cos\theta)^2 Ly^2}{(1 + K^2 - 2K\cos\theta)^2} d\theta dy \text{ watts}$$

The power lost in each element of thickness S and width $rd\theta$ is

$$\frac{0 \cdot 04\pi^2 f^2 \hat{I}^2 \cos^2(2\pi ft)LS^3}{3 \times 10^{16} r\rho} \cdot \frac{(1 - K\cos\theta)^2}{(1 + K^2 - 2K\cos\theta)^2} d\theta$$

If I be the R.M.S. value of the current, the mean power lost is

$$dP = \frac{4\pi^2 f^2 I^2 LS^3}{3 \times 10^{18} r\rho} \cdot \frac{(1 - K\cos\theta)^2}{(1 + K^2 - 2K\cos\theta)^2} d\theta \text{ watts}$$

Therefore the power lost in the whole sheath due to the cicumferential fields is $\int_0^{2\pi} dP$ and entails the integration of the expression

$$[(1 - K\cos\theta)^2/(1 + K^2 - 2K\cos\theta)^2]d\theta$$

This may be written

$$\int_0^{2\pi}\left\{\frac{1}{4} + \frac{1}{4}\frac{(1 - K^2)^2}{(1 + K^2 - 2K\cos\theta)^2} + \frac{1}{2} \cdot \frac{1 - K^2}{1 + K^2 - 2K\cos\theta}\right\}d\theta$$

The second and third of these three integrals are not found in ordinary textbooks and their solution is therefore given in some detail in Appendix I, from which on substituting the limits we find:—

$$\int_0^{2\pi} dP = \frac{4\pi^2 f^2 I^2 LS^3}{3 \times 10^{18} r\rho} \cdot \frac{\pi(2 - K^2)}{1 - K^2}$$

and the watts/cm² of the mean circumference of the lead sheath due to this cause become

$$\frac{2\pi^2 f^2 I^2 S^3 (2 - K^2)}{3 \times 10^{18} r^2 \rho (1 - K^2)} \quad . \quad . \quad . \quad . \quad (a)$$

It will be seen from this expression that as the cables are spaced further and further apart the value of K becomes less and less, so that ultimately the fraction $(2 - K^2)/(1 - K^2) = 2$; and then the eddy loss in the sheath is that usually calculated for one long, straight, independent cable. Under these circumstances also, expression (a) becomes $4\pi^2 f^2 I^2 S^3/(3r^2\rho \times 10^{18})$. This divided by S gives the watts lost per cm³ of the lead sheath. For metal sheets this loss is generally given in terms of the maximum magnetic induction B. Upon substituting in the above expression the obvious relationship $I^2 = r^2 B^2/0{\cdot}08$ we find that the eddy loss in watts/cm³ is $\pi^2 f^2 B^2 S^2/(\rho \times 6 \times 10^{18})$, which is the ordinary formula for the eddy loss in thin sheets.* Thus the proximity of the second cable has the effect of increasing this loss in the ratio $(2 - K^2)/(2 - 2K^2)$.

Our calculation has proceeded thus far on the assumption that in each element of the sheath the distribution of the flux is substantially uniform throughout its thickness. This, as Sir J. J. Thomson has pointed out,† is true only if the product $\pi S\sqrt{(\mu f)}/\sqrt{\rho}$ is small. Now for lead $\mu = 1$, $S = 0{\cdot}25$ (about), and $\rho = 20\,000$ C.G.S. units (about). Thus in Thomson's sense this product is always small, for with a frequency of 50 it is of the order $0{\cdot}04$; whence we conclude that for a lead sheath our assumption is justifiable.

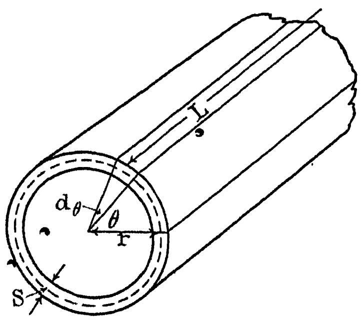


FIG. 2.

Radial field.—Similarly, considering the normal component of the field in the sheath of cable A due to the current in cable B, we have (see Figs. 1 and 2)

$$B_2 = \frac{0{\cdot}2\hat{I} \sin (2\pi ft) \,.\, l \sin \theta}{r^2 + l^2 - 2rl \cos \theta} \quad . \quad . \quad . \quad . \quad (b)$$

The flux through an element of length L and width $rd\theta$ is

$$d\phi_2 = \frac{0{\cdot}2\hat{I} \sin (2\pi ft) \,.\, KL \sin \theta d\theta}{1 + K^2 - 2K \cos \theta}$$

and the flux through an area $Lr\theta$ of the cable sheath is

$$\phi_2 = \frac{L\hat{I} \sin (2\pi ft)}{\cdot 10} \Big[\log (1 + K^2 - 2K \cos \theta) \Big]_0^\theta$$

when θ is measured from the neutral line AB (Fig. 1).

* Cf. *Journal I.E.E.*, vol. 33, p. 951; also STEINMETZ: "Alternating Current Phenomena," 3rd edn., chap. 11.
† See *Electrician*, 8 April, 1892, p. 599.

The distribution of this radial field about the cable is a matter of considerable interest. In Fig. 3 the sheaths of two cables having centres at A and B are indicated by the full and the dotted circles respectively. The full curve about A having two lobes indicates the distribution of radial flux about the cable A due to the current in B. The figure is so drawn that all radial lengths such as CD indicate flux densities along those radii. The lower lobe is really of opposite sign to the upper, but this is not indicated in the figure. The flux density is a maximum at a point on the circumference depending upon the ratio K, and the exact value of θ for this maximum is ascertained by differentiating expression (b) and equating to zero. We thus find:—

$$B_{2max.} \text{ occurs when } \cos \theta = 2K/(K^2 + 1)$$

For the conditions illustrated in Fig. 3 the angle θ at which maximum flux density occurs is 36° 52′ from the horizontal, the lead sheaths being then in contact. As they are separated further and further, K becomes smaller and smaller and the angle gradually becomes

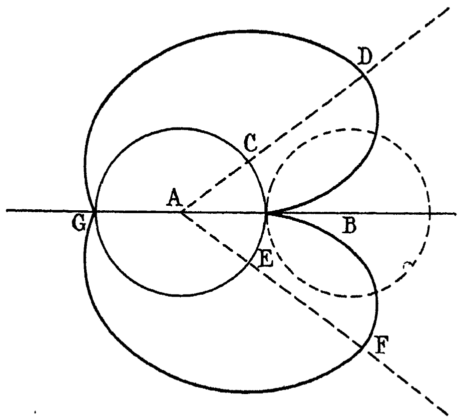


FIG. 3.

greater until $K = 0$, when the cables are at an infinite distance apart and $\theta = \pi/2$. It is clear from this figure that the lines at C and E running along the cable are, as it were, the core centre-lines of the flux lobes, and will stand in a similar relationship as regards eddy currents set circulating in the sheath by variation of this flux; whereby it is also seen that these same lobes might represent to some suitable scale the magnetomotive forces due to the circulating currents. In this manner they illustrate and enforce a principle which is of importance to us and is expressible as follows:—

> If a magnetic field oscillate through a uniform conducting sheet, the eddy currents excited thereby will so distribute themselves as to tend to produce a magnetomotive force distributed in a manner similar to the exciting flux.

From this principle we infer that the eddy-current bands will run lengthwise along the sheath and be zero at C; also that they will be distributed in bands of opposite sign on either side of C and of E, so that between C and E about AB all the current is of one sign return-

ing along the segment between E and C on the side remote from AB.

The flux through a circuit made up of two elementary longitudinal strips of the sheath lying in radial planes displaced by angles θ and $(\pi - \theta)$, respectively, from the plane AB is

$$\frac{L\hat{I}\sin(2\pi ft)}{10}\Big[\log(1 + K^2 - 2K\cos\theta)\Big]_{\theta}^{(\pi-\theta)}$$

$$= \frac{L\hat{I}\sin(2\pi ft)}{10}\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}$$

The E.M.F. acting around the elementary circuit is

$$\delta E = \frac{-2\pi fL\hat{I}\cos(2\pi ft)}{10^9}\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}$$

Neglecting the resistance of the end paths, the section of an element of the circuit is $Srd\theta$, and its length $2L$, so that the resistance of the elementary circuit is $2\rho L/Srd\theta$.

Therefore

$$di = \frac{-2\pi fL\hat{I}\cos(2\pi ft)Sr}{2\rho L10^9}\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}d\theta$$

And

$$dP = \frac{2\pi^2 f^2 L\hat{I}^2\cos^2(2\pi ft)Sr}{10^{18}\rho}\left\{\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}\right\}^2 d\theta$$

Then the power loss due to this cause in the upper semi-cylinder of the sheath is

$$P = \frac{2\pi^2 f^2 L\hat{I}^2\cos^2(2\pi ft)Sr}{10^{18}\rho}\int_0^{\pi/2}\left\{\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}\right\}^2 d\theta$$

This expression when averaged over one period and divided by πrL gives the loss in watts/cm^2 as

$$\frac{2\pi f^2 I^2 S}{10^{18}\rho}\int_0^{\pi/2}\left\{\log\frac{1 + K^2 + 2K\cos\theta}{1 + K^2 - 2K\cos\theta}\right\}^2 d\theta$$

We have not succeeded in obtaining a general solution of this integral, and in consequence we have been compelled to evaluate it for each particular case by a method of numerical integration. The formula adopted and our reasons for choosing it are given in Appendix II, in which is included also a portion of a table of one set of the values calculated.

The power losses as thus deduced are somewhat greater than can ever occur in practice, since we have neglected the effect of the reaction of the eddy currents upon the exciting field, as well as the resistance of the cable ends and the self-induction of the eddy-current circuit. They are therefore to be regarded as limiting values; and if we can show that in all ordinary sizes of cable the total effect as calculated is inappreciable, it follows a fortiori that the cables will be safe in all cases so far as this loss is concerned. In order to arrive at the worst possible case, we remark that the presence of a second cable enhances the loss due to the circumferential field by the multiplier $(2 - K^2)/(1 - K^2)$, i.e. the loss increases as the cables approach one another, up to the limit when their sheaths are in contact. Similarly, examination of the expression for the radial field shows that this also increases up to the same limit—thus the eddy currents are worst when the cable sheaths actually touch.

As regards the question of the relative phase of the currents in the two cables, it is evident that if there is any phase displacement other than π (which is the case just considered), the resultant field in either sheath for a given current is less than the case where there is no phase displacement. The case of 3-core cables is outside the scope of the present inquiry, and has been dealt with elsewhere.* From these considerations we conclude that the worst case for the eddy currents that we are considering occurs when a pair of single-phase, single-core sheathed cables are laid side by side with their sheaths in contact, and for this reason we select for K, for integrating purposes, the value $\frac{1}{2}$.

With regard to the question of size, it will be evident that the greater the size of the core and the smaller the diameter of the sheath, the greater will be the loss; thus low-tension cables are in a much worse position than high-tension cables, and if the losses in the former are small those in the latter will be negligible.

For our table of values we therefore select standard 660-volt paper-insulated cables with standard thicknesses of dielectric and lead sheathing, and taking the six largest of these we calculate the following losses:—

(1) Core copper loss, assuming the maximum current allowable by the I.E.E. Wiring Rules.
(2) Loss due to eddy currents produced by the circumferential field in the case of a pair of cables laid side by side with their sheaths in contact.
(3) Loss due to eddy currents produced by the radial field under the same conditions as (2) above.

Each of the above is then divided by the mean cylindrical surface of the lead covering, giving us the watts/cm^2 which the lead must dissipate in the form of heat produced by each of the three causes; from which it is immediately apparent that the loss due to the circumferential field is in every case entirely negligible. In the last column of Table 1 the loss due to eddy currents is shown as a percentage of the core loss. This figure is the most valuable as it shows by how much the power which the lead has to dissipate is increased by the use of such single-core cables.

In the formulæ as developed it will be noted that all dimensions are in centimetres, but for the convenience of English and American cable makers the values in the table are in the usual English units. The standard English frequency of 50 has been adopted, but for any other frequency the losses may be easily deduced from those given in the table if it is remembered that the loss is proportional to f^2.

* *Journal I.E.E., loc. cit.*

We think that we are justified in drawing the following conclusions from this table :—

(1) The eddy-current losses in the lead sheaths of standard cables due to causes under (A) (page 477) are so small that they cannot even in the worst case materially affect the temperature-rise of the cables.
(2) Standard cables appear to be so proportioned and rated that the copper loss per cm^2 of the sheath surface is about constant. This is to be expected since the currents in col. 2 have been arrived at by the Institution on the basis of a standard temperature-rise, and the whole of the heat has to pass through the surface of the lead sheath.
(3) Of the sheath losses so far considered, those due to the radial field are far greater than those due to the circumferential field. This fact may be of importance when armoured cables are considered.

(1) Case of a Pair of Single-phase Cables.

Here again we take r as the mean radius of the sheath, and l as the distance between the cable centres, K being the ratio r/l.

Then, referring to Fig. 4, the total flux between

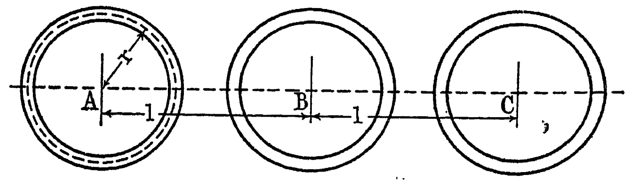


Fig. 4.

the sheaths due to the current $\hat{I}\sin(2\pi ft)$ in one cable and $-\hat{I}\sin(2\pi ft)$ in the other, is

$$\phi = 0\cdot 92\hat{I}\sin(2\pi ft)\log_{10}\frac{1-K}{K} \text{ (per cm length)}$$

Table 1.

Sheath Eddy-current Losses in a Pair of Lead-sheathed Single-phase Cables. Sheaths in Contact.

(ρ for copper $= 1\cdot 78/10^6$ per cm cube; ρ for lead $= 20\cdot 8\times 10^{-6}$ per cm cube; frequency $= 50$.)

Nominal core area	Maximum permissible current (I.E.E.)	Thickness of lead	Mean radius of lead sheath	Copper loss*	Loss due to circumferential field	Loss due to radial field	Ratio: $\frac{\text{Sheath loss}}{\text{Copper loss}}$, per cent
sq. in.	amps.	in.	in.	watt/cm^2	watt/cm^2	watt/cm^2	
1·00	932	0·110	0·8345	0·018	$7\cdot 8\times 10^{-6}$	$579\cdot 5\times 10^{-6}$	3·3
0·75	738	0·100	0·7265	0·01729	$4\cdot 8\times 10^{-6}$	$330\cdot 5\times 10^{-6}$	1·97
0·60	624	0·100	0·6615	0·01696	$4\cdot 2\times 10^{-6}$	$236\cdot 2\times 10^{-6}$	1·44
0·50	540	0·090	0·6085	0·01658	$2\cdot 7\times 10^{-6}$	$159\cdot 2\times 10^{-6}$	0·99
0·40	464	0·090	0·5635	0·01651	$2\cdot 3\times 10^{-6}$	$117\cdot 5\times 10^{-6}$	0·74
0·30	385	0·080	0·4905	0·01743	$1\cdot 5\times 10^{-6}$	$71\cdot 94\times 10^{-6}$	0·43

* Per cm^2 of mean sheath surface.

(4) The percentages given in col. 8, though small, are larger than could occur in practice, since the self-induction of the elementary circuits has been neglected (see page 480).
(5) There is no object in considering any cables smaller than those given in the table.
(6) When the value of K is $<\frac{1}{5}$, the loss decreases rapidly and need not be further considered.

We pass next to a consideration of the eddy currents under (B) (page 477), on the assumption that single-core cables are again used but that they are now spaced apart and have a heavy metal connection at both ends, so that each pair forms a closed circuit enclosing an alternating flux. There are only two cases of any importance that are likely to occur in practice, viz. when two single-phase cables are laid side by side, and when the three cables of a three-phase system are laid side by side with the distance between either outside cable and the middle equal to one-half the distance between the outside cables.

so that the E.M.F. acting around the circuit composed of the two cable sheaths and their bonding is

$$E = -\frac{1\cdot 84\pi f\hat{I}\cos(2\pi ft)}{10^8}\log_{10}\frac{1-K}{K} \text{ (per cm run)}$$

The corresponding resistance, neglecting that of the bonding, is $\rho/\pi rS$. Thus the mean loss per cm^2 of mean sheath surface is

$$p = \frac{3\cdot 386\pi^2 f^2 I^2 S}{4\rho\,.\,10^{16}}\left(\log_{10}\frac{1-K}{K}\right)^2 \text{ watts}$$

$$= SI^2\left(\log_{10}\frac{1-K}{K}\right)^2\times 10^{-7} \text{ watts (nearly) for 50 periods per second.}$$

This is on the assumption that any flux due to one cable *cutting* the other sheath will add nothing to the circulating current, on account of the eddy currents which it will induce in the sheath of that cable. This, although only partially true, is sufficiently near, as will presently be seen.

In Table 2 we have taken the six sizes of cable given in Table 1 and calculated the above loss for five values of K in each size. We have also given the ratio of this sheath loss to the copper loss as a percentage, and the actual distance in inches between the centres of the cables, corresponding to each value of K.

TABLE 2.

Circuit Eddy Losses in a Pair of Standard Single-phase Lead-sheathed Cables.

(ρ for copper $= 1\cdot78 \times 10^{-6}$ per cm cube; ρ for lead $= 20\cdot8 \times 10^{-6}$ per cm cube; $f = 50$.)

Nominal area	K	Eddy-current loss	Ratio: $\frac{\text{Sheath loss}}{\text{Copper loss}}$ per cent	Actual distance, centre to centre
sq. in.		watt/cm²		in.
1	0·01	0·0966	537	83·4
	0·1	0·022	123	8·34
	0·2	0·0088	49	4·17
	0·3	0·0028	16	2·78
	0·4	0·00075	4·2	2·08
0·75	0·01	0·055	318	72·6
	0·1	0·0126	73	7·26
	0·2	0·005	29	3·63
	0·3	0·0019	11	2·42
	0·4	0·00043	2·5	1·81
0·6	0·01	0·039	232	66·0
	0·1	0·009	53	6·6
	0·2	0·0036	21	3·3
	0·3	0·00133	7·8	2·2
	0·4	0·000306	1·8	1·65
0·5	0·01	0·0265	160	61·0
	0·1	0·006	36·6	6·1
	0·2	0·0024	14·6	3·05
	0·3	0·0009	5·4	2·03
	0·4	0·00021	1·2	1·52
0·4	0·01	0·0196	105	56·4
	0·1	0·0045	27	5·64
	0·2	0·0018	11	2·82
	0·3	0·00066	4	1·88
	0·4	0·00015	1	1·41
0·3	0·01	0·012	68·8	49·0
	0·1	0·0027	16	4·9
	0·2	0·0011	6·3	2·45
	0·3	0·0004	2·3	1·63
	0·4	0·00009	0·54	1·22

It is manifest from this table that we have here to deal with a loss which may produce a dangerous heating effect.

We shall postpone the general conclusions derived from this analysis until we have examined the case of three-phase systems, to which we now turn.

(2) CASE OF THREE THREE-PHASE CABLES IN ONE PLANE.

We confine ourselves to this case, because when single-core cables are used it is usually under circumstances where this arrangement is by far the easiest to adopt. Also it may be remarked that the only other likely case is that in which the three cables are arranged with their centres at the points of an equilateral triangle, when the eddy losses do not essentially differ from those in the single-phase case already examined. We therefore suppose that the three cables are arranged as shown in Fig. 4, and K, l and r have the same values as heretofore. The flux between the sheaths of A and B (Fig. 4) will be produced by the currents in A and B, plus so much of the flux due to C as lies between these two sheaths; and this sum, oscillating at a frequency f, will produce an E.M.F. around the circuit composed of A and B and their bonding. In this case, as in the previous one, we suppose that the flux linked with only part of the sheath is producing eddies in the sheath as already calculated, so that no difference of potential exists between A and B on account of it. This is not strictly accurate, but it is quite within the limits of the errors inherent in the calculation.

The E.M.F. arrived at in this way, when squared and divided by the resistance of the two sheaths in series, gives the watts lost due to this cause, but there will be a further loss in cable A due to a similar current flowing along it and returning via cable C. This will be produced by the E.M.F. due to the flux common to A and C. If B did not exist, there would be no difficulty in calculating the value of the current; but its presence renders the result somewhat doubtful. Proceeding, however, on the same assumption as before, viz. that partial linkages do not contribute to the current with which we are now dealing, we may estimate the losses in either A or C. The loss in B is in any case smaller, having the same value as for a single-phase cable carrying a like current, so that the limiting safe distance at which the cables can be spaced is determined by the losses in the outers.

Taking then the currents in A, B and C to be $\hat{I}\sin(2\pi ft)$, $\hat{I}\sin(2\pi ft + 2\pi/3)$ and $\hat{I}\sin(2\pi ft + 4\pi/3)$, respectively, we find that the mean power lost in either A or C due to the current flowing between either and B is

$$\frac{4\pi^2 f^2 \hat{I}^2 S}{2\pi\rho \,.\, 10^{18}}\int_0^{2\pi}\left\{\cos\theta' + \cos\left(\theta' - \frac{\pi}{3}\right)\log\frac{1-K}{K} + \cos\left(\theta' + \frac{\pi}{3}\right)\log\frac{2-K}{1+K}\right\}^2 d\theta'$$

where $\theta' = 2\pi ft$.

Writing the R.M.S. value of the current in either of the three cables as I, we have:—

Mean power lost per cm² of mean sheath surface due to this current

$$= \frac{4\pi^2 f^2 I^2 S}{\rho \,.\, 10^{18}}\left\{3\left(\log\frac{1-K}{K}\right)^2 + \left(\log\frac{2-K}{1+K}\right)^2\right\}$$

Similarly the mean power lost per cm² due to the current common to A and C is

$$\frac{6\pi^2 f^2 I^2 S}{10^{18}\rho}\left\{\log\frac{(1-K)(2-K)}{K(1+K)}\right\}^2$$

The total mean loss per cm² in either outer is therefore

$$\frac{4\pi^2 f^2 I^2 S}{10^{18}\rho}\left\{3\left(\log\frac{1-K}{K}\right)^2+\left(\log\frac{2-K}{1+K}\right)^2 + 1\cdot5\left(\log\frac{(1-K)(2-K)}{K(1+K)}\right)^2\right\}$$

Now the loss in the middle cable may be written :—

$$\frac{16\pi^2 f^2 I^2 S}{10^{18}\rho}\left\{\log\frac{1-K}{K}\right\}^2$$

and by taking a series of values for K we may compare the losses in either of the outers with that in the cable B. This has been done in the following table, from which it will be seen that the ratio of the two is nearly constant, and may for all practical purposes be taken as 1·4.

TABLE 3.

Ratio of Losses (Outer/Middle) for a Three-phase Cable.

K	Ratio
0·4	1·44
0·3	1·42
0·2	1·37
0·1	1·34

These values hold, whatever be the material of the sheath.

GENERAL CONCLUSIONS FOR LEAD-SHEATHED CABLES.

The formulæ developed in this paper are general as regards the material of the sheath, since the specific resistance occurs as a general value, but when applying the expressions to find safe limits for any particular case the corresponding value of ρ must be inserted, as has been done in Tables 1 and 2, and in the summary on page 481. We may now draw the following conclusions :—

(1) In all single-core cables sheath eddies exist. The loss due to them is greatest when the sheaths are closest together, and diminishes as the distance between neighbouring cables is increased.

(2) In the largest low-tension cables made, the sheath eddy loss never exceeds 4 per cent of the copper loss in the core, and consequently is of little importance as a heating effect.

(3) No sheath loss except that due to sheath eddies can exist unless the sheaths are connected at more than one point by conducting material.

(4) With modern switchgear it is not usually possible to avoid connecting at more than one place.

(5) From the point of view of temperature-rise, the question of the length of the run has nothing to do with the advisability of using single-core cables, since so long as they are parallel the loss is proportional to the length, as is also the cooling surface.

(6) The sheath circuit-eddy loss is a far more serious matter than the sheath eddy loss. It is greatest in the outer cables of a parallel three-phase main, and has in that case a value approximately 1·4 times as great as in the case of a single-phase main carrying the same current.

(7) Assuming that it is not desirable that the sum of the sheath and sheath-circuit losses should exceed 10 per cent of the copper loss in the cable, then in laying such cables either metallic connection at more than one place between the sheaths must be avoided, or the distance from centre to centre of standard cables as compared with the mean diameter of the lead sheath should not exceed the following limits :—

Nominal core area	Safe distance, centre to centre	
	Single-phase	Three-phase
sq. in.	in.	in.
1·0	2·2	2·0
0·75	2·2	2·0
0·6	2·2	2·0
0·5	2·3	2·1
0·4	2·6	2·25
0·3	3·1	2·6

These are the most important sizes, and all the figures refer to standard low-tension lead-sheathed paper cables. For smaller areas the safe distance rapidly increases, but for any special case the safe distance can easily be calculated from the formulæ given. It will be noted that in all cases, except the three largest, the allowable spacing falls within the dimensions of standard porcelain cleats in racks, so that the following recommendation may also be added :—

(8) For all cases, both high and low tension, it is safe to use standard porcelain cleat racks for single-core lead-sheathed cables, provided that the core area does not exceed 0·5 sq. in.

It should be noticed that the cases specifically considered in the paper are the worst that can occur in practice, our object being to discover safe limits rather than to tabulate exact losses. In the case of high-tension cables, for example, where the mean radius of the sheath is so much larger as compared with the core diameter, there is no likelihood of serious heating due to sheath losses, unless the spacing of the cables is quite unreasonably large. We should regard 3 inches to 3½ inches as being perfectly safe for all ordinary cases.

On the other hand, to reduce dielectric stresses it is now not unusual to construct high-tension cables with a jute core. In this case the ratio [(mean radius of sheath)/(core diameter)] is reduced again, but so also is the current-carrying capacity of the core. On the whole these two effects leave the general conclusions at which we have arrived unchanged, but special cases must be specially treated. This matter has been fully considered elsewhere,* as well as the sheath circuit eddies produced in a three-phase single-core-cable system with symmetrical spacing.

The chief sources of error in our calculations are those due to neglect of (*a*) bonding resistances, and (*b*) self-induction. The former is indeterminate, dependent upon circumstances, and reducible by care to a negligible quantity. The latter is by no means negligible, and its values have been calculated in the paper already quoted. Its effect is always to reduce the sheath circuit eddy, and thus provide a margin to the limits we have assigned. This margin, however, becomes of practical importance only in high-tension cables where the dielectric thickness is considerable.

There is one other matter for precaution to which we should direct attention. If to avoid sheath circuit eddies the sheaths are not bonded, a considerable E.M.F. may exist between a pair of sheaths, which in the case of high-tension cables may be really dangerous both to the cables and to those handling them. This voltage is easily calculated from the formulæ already given, and its magnitude as well as various methods of earthing to avoid its effects without actually closing the sheath circuit have been discussed by Clark and Shanklin in the paper already referred to. It will be noted that the analysis always points to the desirability of laying the cables as close to one another as possible. Nevertheless, we do not recommend placing them with their sheaths in contact. We think that the best plan is to cover the lead with a serving of jute, tape or braid, in which case the cables may lie in actual contact. Without this precaution it is possible that at the points where lead actually touches lead, pitting may occur and ultimately lead to a breakdown of the sheath. Therefore, if such a serving be not adopted, the cables should be definitely spaced by cleats.

Armoured Cables.

We have not yet considered any case in which the sheath is of magnetic material, for the simple reason that such sheaths almost always take the form of wire or tape armouring. The determination of the resistance to eddy currents of such a sheath is almost impossible except by means of experiment, and a series of tests has been instituted at the Birmingham University to discover the limits in such cases and to supplement the work of Whitehead and Fisher.† These will be published later. In the meantime it seems reasonable to ask, as a result of this investigation, that supply undertakings should withdraw the embargo that in some cases has been laid upon the use of single-core cables for low-tension a.c. systems, and substitute therefor a permission subject to the limitations here set forth. We further think that such limitations might well receive the attention of the I.E.E. Wiring Rules Committee, with a view to including them in the Wiring Rules; and we wish to thank Mr. Julius Frith, a member of that Committee, for drawing our attention to this matter and for suggesting the investigation.

* *Journal of the American Institute of Electrical Engineers*, 1919, vol. 38, pt. 1, p. 917.

† *Journal of the American Institute of Electrical Engineers*, 1909, vol. 28, pt. 2, pp. 737 and 747.

APPENDIX I.

Case (*a*).—$\displaystyle\int_0^{2\pi}\frac{d\theta}{(1+K^2-2K\cos\theta)^2}$. [$(1+K^2)$ being positive and $-(2K)$ numerically less than $(1+K^2)$, and K being not greater than $0\cdot5$.]

Substitute $$\cos y=\frac{(1+K^2)\cos\theta-2K}{1+K^2-2K\cos\theta}\quad . \quad . \quad . \quad (1)$$

Then $$-\sin y dy=\frac{-\sin\theta(1-K^2)^2d\theta}{(1+K^2-2K\cos\theta)^2}\quad . \quad . \quad . \quad (2)$$

Also $\cos y(1+K^2-2K\cos\theta)=(1+K^2)\cos\theta-2K$.

Therefore $$\sin\theta=\frac{(1-K^2)\sin y}{1+K^2+2K\cos y}\quad . \quad . \quad . \quad (3)$$

From (1), as θ varies from 0 to 2π, y varies also from 0 to 2π, whence

$$\int_0^{2\pi}\frac{d\theta}{(1+K^2-2K\cos\theta)^2}$$
$$=\int_0^{2\pi}\frac{-\sin y dy(1+K^2-2K\cos\theta)^2}{-\sin\theta(1-K^2)^2(1+K^2-2K\cos\theta)^2}\quad . \quad (4)$$

Substituting for $d\theta$ from (2), and for $\sin\theta$ from (3), we have

$$(4)=\int_0^{2\pi}\frac{1}{(1-K^2)^3}(1+K^2+2K\cos y)dy$$
$$=\frac{1}{(1-K^2)^3}\Big[(1+K^2)y+2K\sin y\Big]_0^{2\pi}$$
$$=\frac{2\pi(1+K^2)}{(1-K^2)^3}$$

Case (*b*).— $$\int_0^{2\pi}\frac{1-K^2}{1+K^2-2K\cos\theta}d\theta$$

See Todhunter's "Integral Calculus" (1880), p. 278.

APPENDIX II.

Method of evaluating the expression

$$\int_0^{\pi/2}\left\{\log\frac{1+K^2+2K\cos\theta}{1+K^2-2K\cos\theta}\right\}^2d\theta$$

The value of this integral was obtained by a method derived from Newton's interpolation formula.

The general expression is

$$\frac{1}{w}\int_a^{a+rw} f(x)dx = \tfrac{1}{2}f_0 + f_1 + f_2 + \ . \ . \ . + f_{r-1} + \tfrac{1}{2}f_r$$
$$- \tfrac{1}{12}(\delta f_{r-\frac{1}{2}} - \delta f_{\frac{1}{2}})$$
$$- \tfrac{1}{24}(\delta^2 f_{r-1} + \delta^2 f_1)$$
$$- \tfrac{19}{720}(\delta^3 f_{r-\frac{3}{2}} - \delta^3 f_{\frac{3}{2}})$$
$$. \ . \ . \ . \ . \ . \ . \ .$$
$$- \text{etc.}$$

Here f_{-3}, f_{-2}, f_{-1}, f_0, f_1, f_2, f_3, . . ., are the successive calculated values of the function $f(x)$ corresponding to definite constant increments w of the variable x. Also

$$\delta f_{-\frac{1}{2}} = f_0 - f_1,$$
$$\delta f_{\frac{1}{2}} = f_1 - f_0, \text{ and similarly}$$
$$\delta^2 f_1 = \delta f_{\frac{3}{2}} - \delta f_{\frac{1}{2}}, \text{ etc.}$$

The most convenient way of arriving at the integral is to tabulate the successive values of the function and the successive differences in a series of parallel vertical columns, from which the required values are ascertained and then inserted in the formula, in accordance with the general expression. The order of differences up to which the calculation is carried must of course depend entirely upon the rapidity with which the differences decrease as their order increases, and the process is useless unless the series converges. It is assumed that the function and its differential coefficients up to the order of differences employed are continuous, which in the present case is obviously true.

It will be seen that the value of the integral can by these means be obtained to any desired degree of accuracy, which is our reason for preferring it to any of the simpler and more ordinary methods, such as Simpson's or Weddle's rule.

In the case under consideration, the values of the function were calculated for every 10° increase in θ, giving 10 values in all for f_0, f_1, f_2, f_3, etc., so that $w = \pi/18$ radians. The differences were taken as far as the ninth order, the final differences being of the order of 1/125 of the value of f_0. It will be seen, therefore, that the convergence is sufficiently rapid for the accuracy required. Since K is taken as 0·5 the integral required is

$$\int^{\pi/2}\left\{\log\frac{1\cdot 25 + \cos\theta}{1\cdot 25 - \cos\theta}\right\}^2 d\theta$$

and the following table is a small portion of the actual calculation, inserted here to illustrate the method of setting out the values. The figures are logarithms to the base 10.

θ	$f(\theta)$	Δ	Δ^2	Δ^3	Δ^4
0°	0·91056				
		− 0·05366			
10°	0·85690		− 0·08314		
		− 0·13680		0·04925	
20°	0·72010		− 0·03389		− 0·01008
		− 0·17069		0·03917	
30°	0·54941		0·00528		
		− 0·16541			
40°	0·38400				
		etc.	etc.	etc.	etc.

Completing the table in this way and substituting the values derived from it in the formula, together with their appropriate coefficients, the final value of the integral was found to be 3·16385, from which the values in col. 7 of Table 1 in the paper have been calculated.

DIRECTIONS FOR THE STUDY OF PRESSBOARD FOR ELECTRICAL INSULATING PURPOSES.

(REPORT RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.)

CONTENTS.

I. DEFINITIONS AND TERMINOLOGY.

(a) *Definition of Pressboard.*

The term "Pressboard" denotes all materials marketed as Pressboard, Presspahn, or Fullerboard, which materials are made by a paper-making process from vegetable fibres, but differ from papers in that they are made on a "Board" machine, and are afterwards subjected to great pressure in order to remove excess of water and to "close up" the sheet, thus producing a solid board. The boards are afterwards dried, and, if specified, are glazed by calendering and planishing.

NOTE.—Strawboard is not included, as its use is considered undesirable for electrical work.

(b) *Terminology.*

(i) The term "Longitudinal" denotes the direction parallel to that in which the material travelled during manufacture.

(ii) The term "Transverse" denotes the direction at right angles to that described in (i) above.

(iii) The term "Perpendicular" denotes the direction at right angles to the thickness of the material.

NOTE.—When the material is built up of superposed layers having the "grain" at right angles, there is no definite longitudinal or transverse direction.

(c) *Classification of Pressboard.*

Three classes of Pressboard are recognized, as follows :—

Class A.—Hard, non-porous, untreated pressboard, having a density exceeding 1·15 after 18 hours' drying at 80° C., and characterized by a relatively high electric strength.

Class B.—Soft, untreated pressboard having a density less than 1·15, but not lower than 0·90, after 18 hours' drying at 80° C., and consequently having a relatively lower electric strength combined with greater absorption than Class A pressboard.

Class C.—Pressboard impregnated during manufacture with varnish, oil, wax, and the like, or otherwise treated to improve its electrical properties.

II. TESTS.

(1) CONDITIONING OF SPECIMENS FOR TEST.

Before the tests specified in Clauses 2, 3, 4, 5, 13, 14, and 15 are carried out, the specimen shall be dried at a temperature from 75° C. to 80° C. for 18 to 24 hours, and the test shall be conducted as soon as the temperature of the specimen has fallen to 20° C. (± 5° C.).

(2) TENSILE STRENGTH AND EXTENSION.

The specimen shall be conditioned in accordance with Clause 1 before the tests for tensile strength and extension are carried out.

The form and dimensions of the specimen for test shall be as shown in Fig. 1. The thickness of the specimen shall be the thickness of the material.

The specimen shall be tested to ascertain the ultimate tensile strength and extension on a three-inch gauge length.

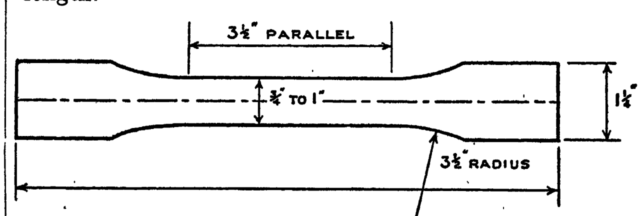


FIG. 1.—Specimen for Tensile Strength and Extension Tests.

The load shall be increased steadily at such a rate that the specimen breaks in about two minutes from the time of the application of the load.

The ultimate tensile strength shall be expressed in lb. per sq. in. (kg per cm²). The extension shall be expressed as a percentage on the original gauge length.

(3) COMPRESSION STRENGTH.

The specimen shall be conditioned in accordance with Clause 1 before the compression strength test is carried out.

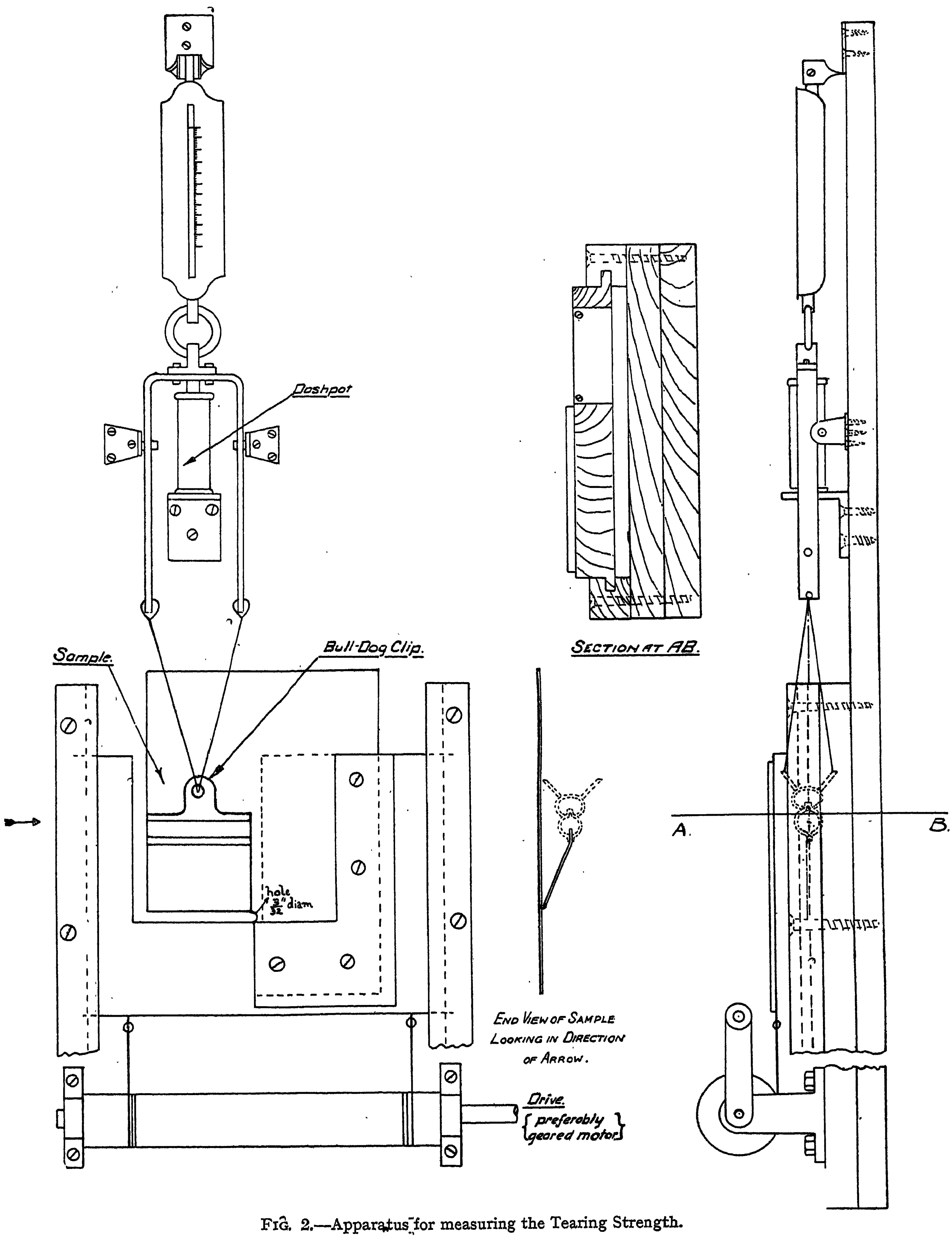


FIG. 2.—Apparatus for measuring the Tearing Strength.

The form of the specimen for test shall be either a cylinder 1 inch long and 3 inches diameter, or a prism 1 inch long and 3 inches square, the specimen being built up with sufficient layers of the material.

The compression faces of the testing machine shall be 2 inches diameter.

The specimen shall be set up for testing so that its centre line is co-axial with the centres of the compression faces of the testing machine.

The layers of the material shall be bedded together by the application of an initial load of 100 lb. per sq. in., and the first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

A series of tests shall then be carried out by the application of increasing loads, in steps of 1 500 lb. per sq. in., each of which shall be maintained for one minute; and the yield of the specimen shall be measured at the end of each period. The tests shall be continued until the specimen has yielded 25 per cent of its original length when measured as stated above, or the load has reached about 6 tons per sq. in.

(4) Shearing or Tearing Strength.

The specimen shall be conditioned in accordance with Clause 1 before the test for shearing or tearing strength is carried out.

(*a*) *Shearing Strength.*

Materials above 1/32 inch (0·8 mm) thick up to and including $\frac{1}{8}$ inch (3·2 mm) thick shall be tested to ascertain the pressure required to punch a hole $\frac{1}{2}$ inch diameter.

The load shall be applied steadily, and shall be increased at a rate of about 100 lb. per minute for each 1/32 inch thickness of the specimen.

The clearance between the punch and the die shall be negligible, as obtained by trimming the punch with the die.

The pressure required to punch the hole shall be expressed in lb. per sq. in. (kg per cm^2).

Materials above $\frac{1}{8}$ inch (3·2 mm) thick shall be tested as follows:—

A specimen, the dimensions of which shall be 5 inches (127 mm) long, and $2\frac{1}{2}$ inches (64 mm) wide, shall be clamped in a shear testing machine so that both ends of the specimen are sheared off simultaneously. The pressure required to produce shear shall be computed on the total area of the sections sheared, and shall be expressed in lb. per sq. in. (kg per cm^2).

(*b*) *Tearing Strength.*

Materials up to and including 1/32 inch (0·8 mm) thick shall be tested for tearing strength as follows:—

The form and dimensions of the specimen for test shall be 6 inches square.

The tearing strength shall be the load required to tear the specimen commencing from a hole 3/32 inch (2·4. mm) diameter punched out of the specimen. The position of the hole and the application of the load shall be as shown in Fig. 2.

Three longitudinal and three transverse tear tests shall be carried out on each material under test. The maximum, mean and minimum values shall be stated.

The load required to tear the specimen shall be expressed in lb. (grammes).

(5) Cohesion between Layers (Splitting Test).

The specimen shall be conditioned in accordance with Clause 1 before the test for cohesion between layers is carried out.

Cohesion between layers shall be tested by one of the following methods:—

(*a*) A specimen shall be cut to the following dimensions:—

Width = 1 inch.
Thickness = Thickness of the material.
Length = Four times the thickness plus $\frac{1}{2}$ inch.

The specimen shall be supported on V supports spaced apart at a distance equal to four times the thickness of the material under test. A load shall be applied centrally on the specimen and increased until failure occurs. The load required to produce failure and the nature of the fracture shall be stated.

(*b*) A specimen 2 inches square shall be tested to ascertain whether it is possible to split the material parallel to the laminations, when a split has been started at one corner by the insertion of a knife.

(6) Flexibility (Bending Test).

Flexibility Tests shall be carried out on the material as follows:—

(*a*) *Cold* (*before Baking*).

Each specimen of every thickness up to and including 0·020 inch shall be bent longitudinally and transversely flat on itself, and the effect at the bend shall be stated.

Each specimen of every thickness above 0·020 inch shall be bent longitudinally and transversely through an angle of 90°, and the effect at the bend shall be stated. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 1 below:—

Table 1.

Limits of Thickness of Specimen, inch	Diameter of Pin, inch
Above 0·020 up to and including 1/32 ..	$\frac{1}{4}$
Above 1/32 up to and including 1/16 ..	$\frac{3}{8}$
Above 1/16 up to and including $\frac{1}{8}$	$\frac{1}{2}$

(*b*) *After Baking.*

The specimen shall be heated at a temperature from 105° C. to 110° C. for 48 hours, and shall then be bent longitudinally and transversely through 90°, and the effect at the bend shall be stated. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 2 below.

TABLE 2.

Limits of Thickness of Specimen, inch	Diameter of Pin, inch
Up to and including 0·010 ..	$\frac{1}{8}$
Above 0·010 to 0·020 ..	$\frac{3}{16}$
Above 0·020 to 1/32 ..	$\frac{3}{4}$
Above 1/32 to 1/16	$1\frac{1}{4}$
Above 1/16 to $\frac{1}{8}$	2

(*c*) *After Heating in Oil.*

The specimen shall be heated in transformer oil, complying with British Standard Specification No. 148 for light grade oil, at a temperature from 115° C. to 120° C. for 48 hours, and shall then be bent longitudinally and transversely through 90°. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 3 below. The effect on the specimen shall be stated.

TABLE 3.

Limits of Thickness of Specimen, inch	Diameter of Pin, inch
Up to and including 0·010 ..	$\frac{1}{2}$
Above 0·010 to 0·020 ..	1
Above 0·020 to 1/32 ..	$1\frac{1}{4}$
Above 1/32 to 1/16	$1\frac{3}{4}$
Above 1/16 to $\frac{1}{8}$	2

RESEARCH TESTS.

(7) ELECTRIC STRENGTH.

NOTE.—The following methods for the determination of the electric strength are recommended when the characteristics of the pressboard are not known, and when a thorough investigation is required to ascertain the electric strength of the material under probable service conditions.

(*a*) *General.*

It is of primary importance that the recognized electric strength be that of the material when hot and under long continued stress.

It is desirable to test pressboard at temperatures appreciably above its intended working temperature.

(*b*) *Conditioning of Pressboard previous to Test.*

As the electric strength of pressboard is largely influenced by the moisture content, the characteristic curves referred to later shall be obtained for as many as possible of the following conditions :—

(i) *Normal Condition.*—This is obtained by permitting the pressboard to absorb its normal quantity of moisture by exposing it to an atmosphere of 75 per cent relative humidity at a temperature between 15° C. and 25° C. for 18 to 24 hours.

(ii) *Dry Condition.*—This is obtained by removing from the pressboard as much as possible of its free natural moisture by heating it at a temperature between 75° C. and 80° C. for 18 to 24 hours.

(iii) *Damp Condition.*—This is obtained by exposing the pressboard to an atmosphere of 100 per cent relative humidity at a temperature between 15° C. and 25° C. for 18 to 24 hours.

(iv) *Tropical Condition* (*for use when required*).—This is obtained by exposing the pressboard to an atmosphere of 100 per cent relative humidity at a temperature between 45° C. and 50° C. for 18 to 24 hours.

NOTE.—If in (ii) or (iii) the pressboard is removed from the atmosphere of specified humidity before testing, precautions must be taken to prevent appreciable change in electric strength from this cause.

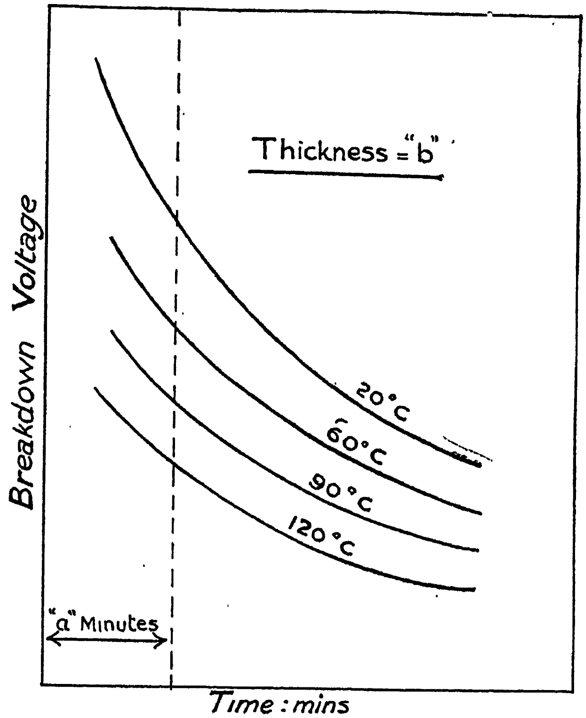


FIG. 3.—Time-voltage Curves at Various Temperatures.

When testing pressboard at the temperatures given in paragraph (*f*), the electrodes should be raised to the high temperature before the material is removed from the atmosphere of specified humidity.

(*c*) *Tests in Air or Oil.*

The electric strength tests on pressboard shall be carried out in air unless the material is intended for use in oil-immersed apparatus when tests under oil are permissible. In the case of pressboard intended for use in air and also in oil-immersed apparatus the effect of subjection to a damp atmosphere (paragraph

(*b*) (iii)) on the electric strength shall be ascertained in air and in oil.

(*d*) *Method of Expressing Electric Strength.*

A single value for the electric strength of pressboard is of practically no use unless the time of application of the voltage, the temperature, and the thickness of the material are either stated or clearly indicated.

Instantaneous values obtained on a rapidly applied test are usually very high and misleading, being out of all proportion to the electric strength obtained by the sustained conditions of practice.

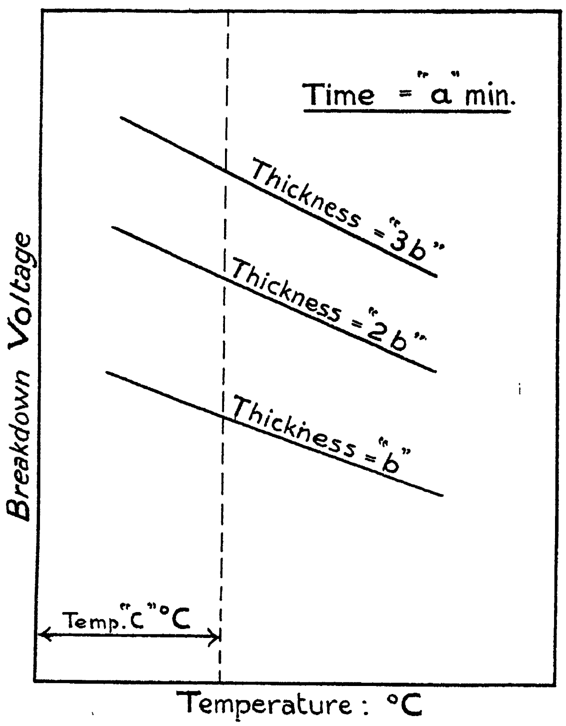


Fig. 4.—Temperature-voltage Curves for Various Thicknesses.

The electric strength shall be given in the form of a series of curves, in which the actual breakdown voltage, R.M.S. value, is plotted against time and temperature; as shown in Figs. 3 and 4 respectively, and the volts per mil against thickness as shown in Fig. 5.

(*e*) *Time-voltage Curves.*

(i) Electric strength tests shall be carried out so as to obtain time-voltage curves showing the breakdown voltage over the time range from half a minute to the time required for the breakdown voltage to become approximately independent of the time.

Note.—When the specimen is tested hot the time required for the breakdown to become approximately independent of the time of application of the voltage may be about 10 minutes. When, however, the tests are carried out at air temperatures (about 20° C.) the time may be considerably longer.

(ii) In special cases transient voltage tests may be desirable.

(*f*) *Temperature-voltage Curves.*

Time-voltage curves shall be obtained for the following temperatures :—

20, 60, 90, and 120° C. (see Fig. 3).

For a selected number of time values on the time-voltage curves a temperature-voltage curve shall be drawn similar to Fig. 4.

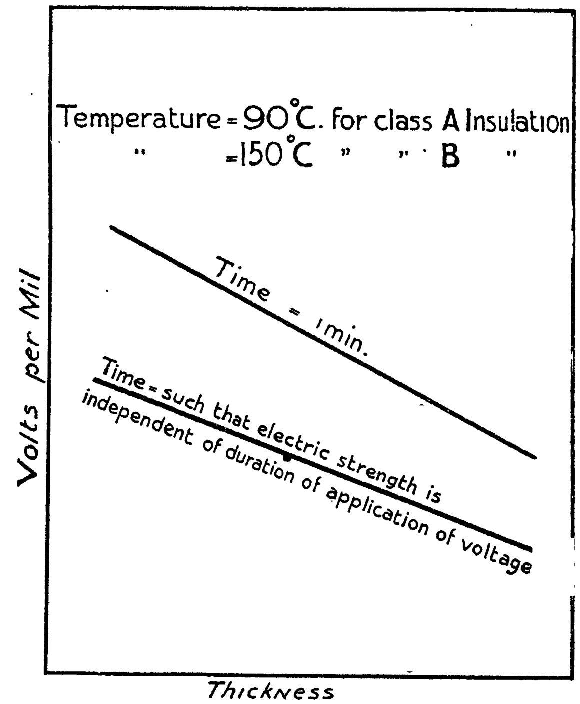


Fig. 5.—Curves showing the relationship between Electric Strength and Thickness.

(*g*) *Thickness-voltage Curves.*

(i) When the pressboard is supplied in more than one thickness sufficient temperature-voltage curves (Fig. 4) shall be obtained to enable the thickness-voltage curve to be plotted for definite time and temperature conditions (see Fig. 5).

(ii) One of the thickness-voltage curves shall be plotted from the one-minute values and another from the values at which the breakdown voltage is approximately independent of the time (x) during which the voltage is applied (Fig. 5).

Note.—For both the above curves the recognized standard temperature is 90° C. for B.E.S.A. Class A insulation.

In plotting the thickness-voltage curves, the values on the vertical axis should be expressed in volts per mil, and not in terms of breakdown voltages.

(*h*) *Calculation of Electric Strength.*

(i) *Curves.*—For drawing the time-voltage curves sufficient tests shall be made to enable fair curves to be drawn over the time range under investigation.

In order that some indication may be given of the uniformity of the material, all the experimental values shall be shown, and when considerable variation is found, this fact shall be specially mentioned.

NOTE.—As the temperature-voltage curves are taken from the mean curves drawn through the values obtained on the time-voltage tests, the experimental points can-

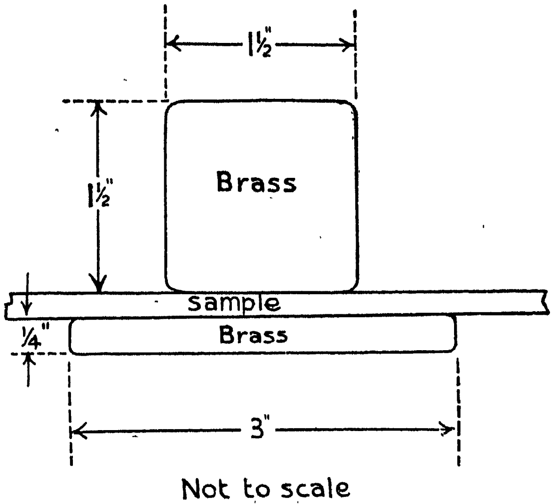


FIG. 6.—Electrodes for Electric Strength Test.

not be indicated on these or on the thickness-voltage curve.

(ii) *Measurement of Thickness.*—The thickness of the pressboard shall be determined, as specified in Clause 14, by means of a suitable micrometer.

(*j*) *Test Equipment.*

(i) *Output of Testing Set.*—The output of the testing set shall be sufficient to maintain on the sample under test the necessary voltage for the maximum period required.

(ii) *Frequency, Wave Shape, etc.*—The frequency of the supply voltage shall be approximately 50 cycles, and if different its value shall be stated. The wave shape shall be as near sinusoidal as possible, and the conditions of the test such as to prevent any high-frequency oscillations.

NOTE.—In carrying out electric strength tests the voltage should be increased smoothly, preferably by means of a suitable resistance in series with the field of the alternator. When the voltage is varied by means of a resistance in series with the primary of the testing transformer the wave shape is liable to be distorted. If the wave shape is not known to be satisfactory, it should be checked whilst a sample is under test, and near the point of breakdown, by means of either a spark gap or a crest voltmeter.

(*k*) *Electrodes.*

The bottom electrode shall consist of a flat disc of brass 3 inches diameter by ¼ inch thick.

The top electrode shall consist of a solid cylinder of brass 1½ inches diameter by 1½ inches long.

The sharp edges shall be removed from the electrodes, but the radius at the edge shall not exceed 1/32 inch (see Fig. 6).

NOTE.—If the surface of the pressboard is irregular, or any difficulty is experienced in obtaining good contact, tinfoil should be interposed between the electrodes and the dielectric.

ABRIDGED TESTS.

NOTE.—The following methods for the determination of the electric strength of pressboard are recommended when it is not required to ascertain the characteristics of the material under all of the conditions provided for above.

(*l*) *Conditioning.*

(i) Prior to test the materials shall be exposed to the "Normal" atmosphere as described in paragraph (*b*) (i).

(ii) If it is claimed that the pressboard has special non-absorptive properties, it shall also be tested after exposure to either "Damp" or "Tropical" conditions, as described in paragraph (*b*) (iii) and (iv).

(*m*) *Method of Expressing Electric Strength.*

The recognized method of expressing the electric strength of pressboard subjected to these abridged tests shall be the voltage required to produce breakdown in one minute when the material is at a temperature of 90° C. For ease of comparison the volts per mil, followed by a statement of the thickness to which it refers, shall also be given.

NOTE.—In the past it has usually been the practice to take the electric strength of an insulating material at air temperature, and by a rapid application of the voltage. Until the recognized standard of one minute at 90° C. has come into general use, it may occasionally be desirable for comparative purposes to determine also the electric strength when the voltage is rapidly applied at air temperature.

(*n*) *Time-voltage Curves.*

In order that the voltage required to produce breakdown in one minute may be accurately determined, the following procedure shall be adopted :—

A test shall be carried out by increasing the voltage as fast as is consistent with obtaining satisfactory readings of the measuring instrument. The pressboard shall then be subjected to two-thirds of the breakdown voltage obtained on a rapidly applied test, and the time required to produce breakdown noted.

From the results of this test an approximate value can be obtained of the voltage that will produce breakdown in about one minute; and this estimated voltage shall then be applied and the time required to produce breakdown noted. From this latter result a still closer approximation can be made. In addition to the rapidly applied test, at least five punctures shall be obtained on each sample and the values plotted on a time-voltage curve, similar to Fig. 3, but for the time range round one minute only. From the curve the voltage required to produce breakdown in one minute can be determined.

(*o*) *Other Factors.*

In conducting the abridged tests for electric strength, the conditions specified for the other factors entering into electric strength tests are the same as for the research tests dealt with above.

(8) Shrinkage and Swelling.

A specimen 6 inches square shall be cut from the material as received, and the length, width, and thickness measured.

The length and width respectively of the specimen shall be the mean of ten measurements taken at points equally spaced along each of two edges at right angles.

The thickness of the specimen shall be the mean of ten measurements of thickness taken at points equally spaced around the edges. The measurements shall be made by means of a micrometer or other suitable method.

Shrinkage shall be determined by the following methods :—

(*a*) The specimen shall be dried for 48 hours by heating uniformly in an oven at a temperature from 105° C. to 110° C., and the length, width, and thickness shall then be measured as above.

Comparison shall be made between the mean values of the dimensions before and after the heat treatment, and the percentage difference computed on the original mean values respectively shall be stated, the original mean values being given.

(*b*) The diameters of a ring approximately 4 inches internal diameter and 6 inches external diameter shall be measured longitudinally and transversely. The ring shall be immersed in transformer oil, complying with British Standard Specification No. 148 for light grade oil, at a temperature from 105° C. to 110° C. for 120 hours. The diameters shall then be re-measured as before at atmospheric temperature. Comparison shall be made between the values of the diameters before and after the immersion in oil, and the percentage difference computed on the original values shall be stated.

The thickness of the ring shall be measured at ten equidistant points around the circumference before and after the immersion in oil. Comparison shall be made between the mean thicknesses before and after the immersion in oil, and the percentage difference computed on the original mean thickness shall be stated, the original mean thickness being given.

Swelling shall be determined by the following method :—

The square specimen used in the shrinkage test shall be exposed to a jet of steam at a temperature from 105° C. to 110° C. for 6 hours and the thickness re-measured as before.

Comparison shall be made between the mean thicknesses before and after the exposure to steam, and the percentage difference computed on the mean thickness after drying shall be stated.

(9) Freedom from Chemical Reaction.

The material shall be tested for freedom from acids and alkalis in the following manner :—

Cut up 30 to 40 grammes of the dried material into small pieces, care being taken to separate the various layers thoroughly. Weigh off duplicate samples of 10 grammes each, introduce each into a 250 cm³ flask and add 200 cm³ of distilled water. Boil gently for about one hour, allow the solution to cool, and then filter at the pump. Wash each sample of pulp twice with 75 cm³ of warm distilled water, then titrate the filtrates, using methyl orange as indicator, employing one sample for the acidity test and the other for the alkalinity test.

The solution shall show no sign of acidity.

If the indicator shows the solution to be alkaline, titrate (neutralize) it with a standard centi-normal solution of hydrochloric acid :—

$$\left(\frac{N}{100}HCl\right)$$

The pulp shall be again similarly treated repeatedly until the filtrate requires only 2 or 3 cm³ of—

$$\frac{N}{100}HCl$$

to neutralize it. A "Blank Test" of the water shall be made in a similar manner and allowed for if necessary.

The number of cm³ of the standard centi-normal solution of hydrochloric acid $\left(\frac{N}{100}HCl\right)$ required to neutralize 10 grammes of the material shall be stated.

Note I.—The presence of glue or albuminous matter may vitiate the result to some extent.

Note II.—The test specified above indicates mineral acids only. If the total acidity of the material is required, including organic acids which may be present, the method outlined above should be slightly modified by boiling the material in methylated spirit instead of in distilled water, and by titrating with phenolphthalein in place of methyl orange.

(10) Freedom from Conducting Particles and Pinholes.

These tests shall be carried out by one of the following methods :—

(*a*) *Thick Materials.*

In the case of materials thicker than 1/16 inch, a specimen 6 inches × 4 inches shall be photographed

by X-rays. The number of metallic particles and pinholes per square foot shall be stated.

(*b*) *Thin Materials.**

In the case of materials up to and including 1/16 inch thick specimens not less than 12 inches square shall be tested by the following methods :—

(i) The specimen shall be saturated with a dilute solution of hydrochloric acid, specific gravity approximately 1·1, and then immersed in a potassium ferricyanide solution to precipitate the iron present. Each iron particle will produce a blue spot on the paper.

The number of deeply stained particles per square foot of the specimen shall be stated.

(ii) A 1 per cent solution of silver nitrate shall be applied to the surface of the specimen. Each metallic particle will produce a black spot on the specimen.

The number of black spots per square foot of the specimen shall be stated.

(iii) The specimen shall be dipped into a 1 per cent solution (by volume) of acetic acid, and then allowed to air-dry for one hour while lying flat on a cloth.

When dry the specimen shall be dipped again in a solution containing 0·1 cm^3 acetic acid and 0·1 gm of potassium ferricyanide in 100 cm^3 distilled water.

Each metallic iron particle will produce a blue spot on the specimen, and each copper, brass, or gunmetal particle a red spot.

The number of blue and red spots respectively per square foot of the specimen shall be stated.

NOTE.—The potassium ferricyanide solution should be tested before use with some precipitated ferric hydroxide dissolved in strong nitric acid, and diluted with water. The potassium ferricyanide solution should give no blue precipitate or coloration.

(11) FREEDOM FROM SUPERFICIAL DEFECTS.

The surface of the material shall be examined and its condition with regard to smoothness, uniformity, freedom from cracks, flaws, and other superficial defects shall be stated.

(12) EFFECT OF OIL.

A specimen shall be immersed in transformer oil complying with British Standard Specification No. 148 for light grade oil for seven days continuously at a temperature from 100° C. to 105° C., and shall then be bent longitudinally and transversely through 90°. The diameter of the pin round which the specimen is bent shall be in accordance with the appropriate value given in Table 4 below. The effect on the specimen shall be stated.

(13) WATER ABSORPTION.

The specimen shall be conditioned in accordance with Clause 1 before the test for water absorption is carried out.

A specimen 3 inches square shall be weighed. The specimen shall then be immersed in water at room temperature. After 24 hours' immersion it shall be taken from the water and, after removing the surface moisture by wiping, weighed again.

The specimen shall then be replaced in the water, and after six days' immersion re-weighed with the same precautions as before. The weight shall be taken to the nearest milligramme in each case.

The percentage absorption of water in each case shall be computed on the original weight of the specimen.

(14) DETERMINATION OF THICKNESS.

The specimen shall be conditioned in accordance with Clause 1 before the thickness is measured.

TABLE 4.

Limits of Thickness of Specimen, inch	Diameter of Pin, inch
Up to and including 0·010 ..	½
Above 0·010 to 0·020 ..	1
Above 0·020 to 1/32 ..	1¼
Above 1/32 to 1/16	1¾
Above 1/16 to ⅛	2

Measurements of thickness shall be made by means of a suitable micrometer at ten points equally spaced around the sides of the sheet. The maximum, minimum, and mean values of thickness shall be stated.

(15) DETERMINATION OF DENSITY.

The specimen shall be conditioned in accordance with Clause 1 before the density is determined.

The density expressed in terms of weight in grammes per cm^3 shall be ascertained by weighing a specimen 3 inches diameter, or 3 inches square. The usual precautions shall be observed in weighing the specimen, and the weight shall be taken to the nearest milligramme.

The area of the specimen shall be computed, in the case of the disc, from the mean of ten measurements of the diameter at equidistant points around half the circumference, and in the case of the sheet from the mean of ten measurements of the length and the width respectively at points equally spaced along each of two edges at right angles. The thickness shall be determined by making ten measurements with a suitable micrometer equally spaced around the circumference in the case of the disc, and around the sides in the case of the sheet, and the mean value shall be taken in computing the volume of the specimen.

* The hydrochloric acid in test (i) has a tendency to act upon the iron oxides present, thus producing considerable discoloration of the specimen. Test (i) does not readily disclose the presence of copper and brass particles.

Test (ii) detects iron, copper, and brass particles, but it is not sufficiently penetrating especially when testing a dark specimen, and metallic particles well inside the sample may not be disclosed. Also, after a short time the discoloration extends throughout the specimen, thus causing difficulty in detecting the metallic particles.

III. APPENDIX.

METHOD OF ASCERTAINING THE ELECTRIC STRENGTH OF PRESSBOARD WHEN SUBJECTED TO LONG APPLICATION OF A.C. STRESS.

When in service in electrical machinery and apparatus, the pressboard has to withstand voltage stresses for long periods of time. As the pressboard is usually in contact with metal parts, which, on account of the energy losses in the copper and the iron, are at a higher temperature than the insulation, the conditions are such that any heat generated in the pressboard itself cannot be readily dissipated.

To investigate the internal heating produced in pressboard when under A.C. stress, and to ascertain the highest A.C. stress which the material can endure without loss of insulating property as the result of excessive internal heating, the following test is recommended :—

(*a*) *Apparatus Suggested.*

In Fig. 7 is shown a diagram of the connections of the necessary apparatus. Particulars of a set of instruments that have been used for this test are given below :—

A.C. Voltmeter.—Electrostatic, reading to about 120 volts, capable of being connected across various sections of a suitable potential dividing resistance connected across the transformer secondary.

NOTE.—Any other type of high-voltage measuring equipment may be used.

D.C. Voltmeter.—Reading up to 150 volts in scale divisions of 1 volt.

Microammeter.—For measurement of leakage current.
Robert W. Paul, London, N.K. 1 035.
Resistance : about 900 ohms at 20° C.
Range : 0–24 microamps, by 0·2 (120 scale divisions).

NOTE.—If the A.C. component is large an instrument of low resistance may be desirable.

Thermocouple.—Eureka—copper.

$6\frac{1}{2}$ inches each of 0·008 inch covered wire and hard soldered to form couple. At the other end the copper is soldered to 3 feet 8 inches of 0·027 inch covered copper wire, and the eureka to 3 feet 8 inches of 0·018 inch covered eureka wire.

From here copper flexible leads are connected to the instrument.

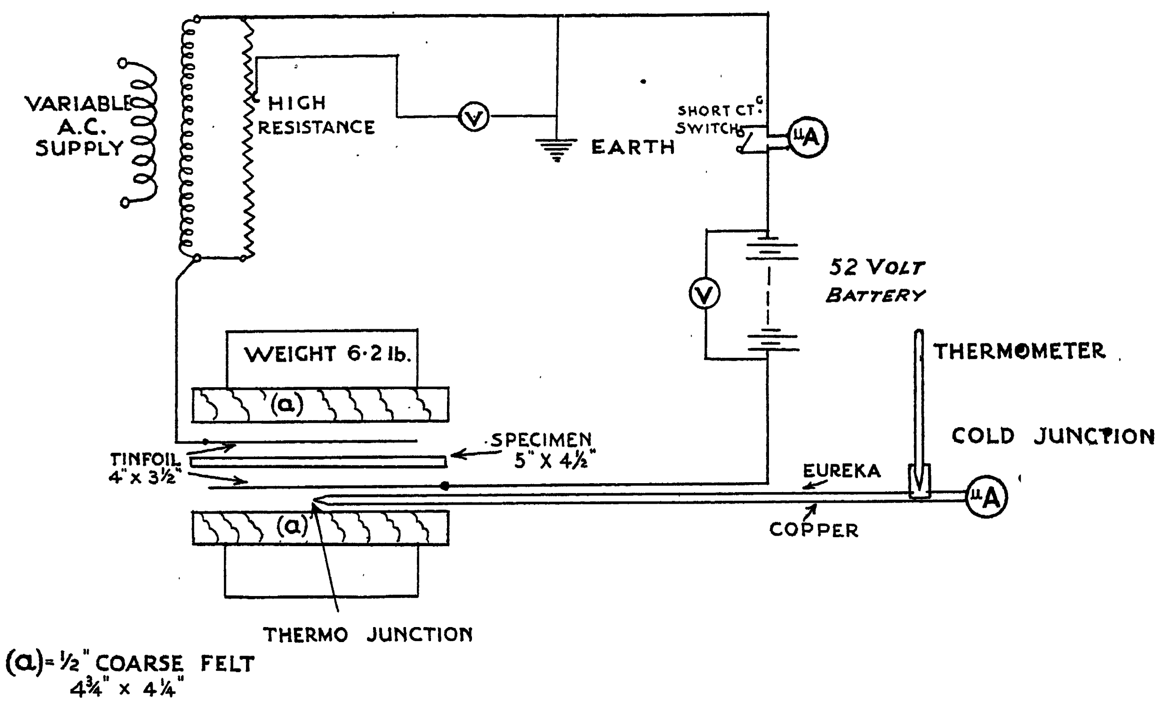


FIG. 7.—Connections for ascertaining the Electric Strength of Pressboard when subjected to Long Application of A.C. Stress.

A thermometer is bound to the cold junction with tape.

Resistance = 4·734 ohms at 20° C.

A eureka series resistance can be inserted to increase the range, but this is not required except for readings in the unstable range.

Resistance of couple and series resistance = 8·65 ohms at 20° C.

Thermocouple Instrument.—Microammeter by Robert W. Paul, London, N.I. 1 135.
Resistance = 5·1 ohms at 20° C.
Range, 0–300 microamps by 5 (60 scale divisions).
Temperature range :
Without series resistance : 0 to about 65° C. rise.
With series resistance : 0 to about 90° C. rise.

Air Temperature.—By thermometer 3 inches from edge of specimen, with bulb on the same level.

Felt Pads.—Coarse green felt, 4¾ inches × 4¼ inches × ½ inch.

Tinfoil.—4 inches × 3½ inches × 0·0015 inch thick.

(*b*) *Arrangement of Test*.

The material is cut into rectangles, each 5 inches × 4½ inches, and exposed to "Normal" * condition (Clause 7 (*b*) (i)). After conditioning, sufficient of these to form a pad approximately 30 mils thick are carefully laid and pressed together so as to exclude entrapped air. On each side of the pad a tinfoil 4 inches × 3½ inches is pressed into contact. The specimen with its tinfoils is placed between two 4¾ inch × 4¼ inch pads of ½ inch coarse felt, and mounted for test as shown in Fig. 7. A thermocouple in contact with the centre of the lower tinfoil measures the temperature attained. In series with the source of high-voltage A.C. are a D.C. battery of (usually) 52 volts and a microammeter by which unidirectional leakage current is measured.

(*c*) *Method of Test*.

An A.C. stress of definite moderate gradient (volts per mil thickness) is applied and maintained until temperature and leakage current attain steady values. The gradient is then increased, and again held until results are steady. This procedure is repeated until a gradient is reached at which temperature and leakage current will not settle down to steady values, but rapidly increase to a destructive condition. At this stage, unless interrupted, charring and complete breakdown rapidly follow. The microammeter should be short-circuited, or the voltage switched off before breakdown of the specimen takes place.

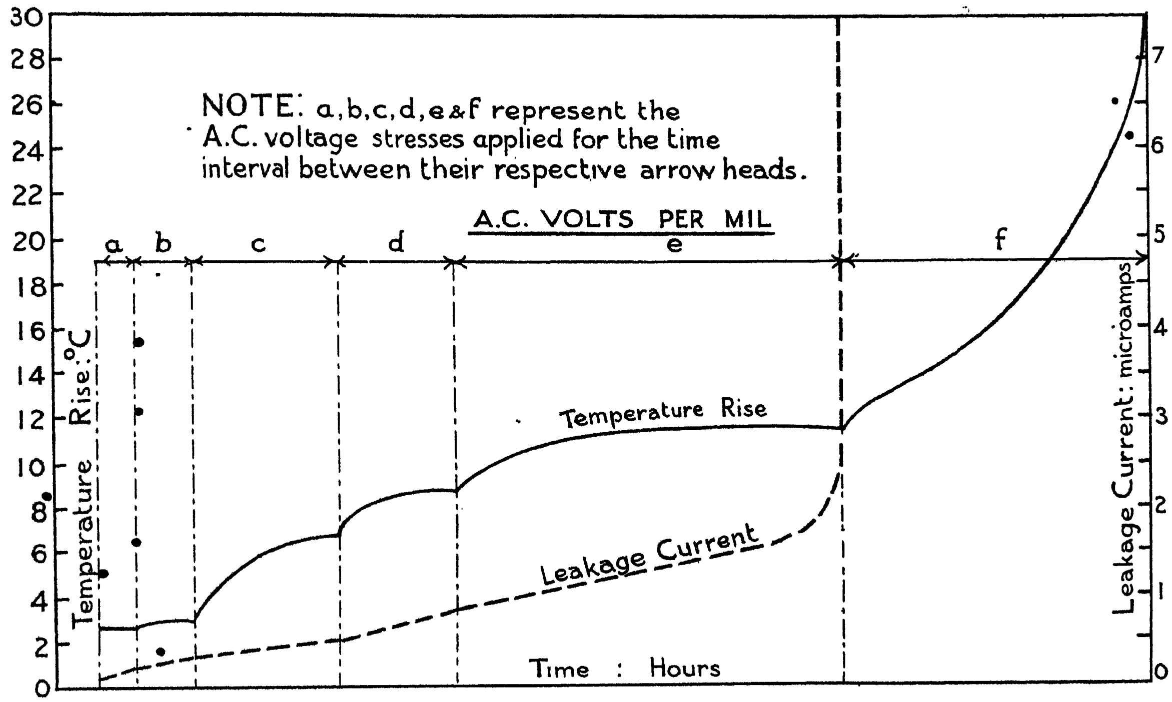


FIG. 8.—Method of expressing the Results of the Test shown in Fig. 7.

(*d*) *Method of Expressing Results Obtained*.

The values obtained should be shown graphically as illustrated in Fig. 8. The following should also be recorded :—

(i) Maximum voltage and electric stress in volts per mil, at which the material is in a stable condition.

(ii) Maximum temperature-rise obtained in (i).

* If it is claimed that the pressboard has any special non-absorptive properties, tests should also be made on specimens that have been exposed to "Damp" or "Tropical" conditions respectively (clause 7 (*b*) (iii) and (iv)).

DISCUSSION ON

"THE INTERCONNECTION OF ALTERNATING-CURRENT POWER STATIONS." *

WESTERN CENTRE, AT CARDIFF, 6 NOVEMBER, 1922.

Major E. I. David: This paper is particularly interesting to the engineers of this district, where a number of interlinking schemes between power stations are under consideration. After seeing the large-scale maps of the enormous distribution schemes in America, one feels how trivial are local schemes in proportion to these, but the actual problems to be solved are very similar, and the paper is most helpful for that reason. I think that the line between Britannia and Aberaman was the first extra-high-tension line between two fair-size power supply systems in this country. At present operating at 20 000 volts, it is designed for 33 000 volts, and will shortly be changed over to that voltage. It connects two systems, one having six power stations and the other two, these being interlinked by their own systems. Power factor control is effected by means of a booster available at one end. In connection with this line an interesting series of figures were taken, and these are shown in Fig. J. The line was run with the receiving end open-circuited, but both step-up and step-down transformers, and also the booster, were in circuit. The pressure at the receiving end was varied by altering the boost from minus 105 volts through zero to plus 185 volts, the voltage at the generating end varying from 3 145 volts to 3 435 volts due to this variation of boost, and the busbar voltage being maintained constant at 3 250 volts. Under the latter conditions the pressure at the receiving end was 10 650 volts, the transformer secondary ratio at this end being normally 20 000/10 000, and 3 000/20 000 at the step-up end. The astonishing fact is that a magnetizing current as high as 395 amperes was required for the line under maximum boost conditions. As the energy losses were very small, the power factor meter of the line was practically at zero throughout the whole of the test. The station load was approximately 4 000 kW and the station power factor varied in the manner shown in the figure. The only possible explanation which I can give for this enormous magnetizing current is saturation of the iron in the transformers, as the latter were running at approximately 15 per cent above their rated voltage. Perhaps the authors can give some additional information. The one fact clearly illustrated by the paper is that, provided a station has any means of fixing its busbar voltage, the power factor of the supply which it takes, either from an interconnecting line or from an ordinary supply company's main, is entirely independent of the power factor of its own load, and as the general policy of station engineers is to carry as little wattless current as possible, the result will be to maintain such a busbar voltage that the generating station power factor will be as near unity as possible, and the supply company will have to deal with this. Unless, therefore, the busbar voltage of all interconnected stations is under the control of the

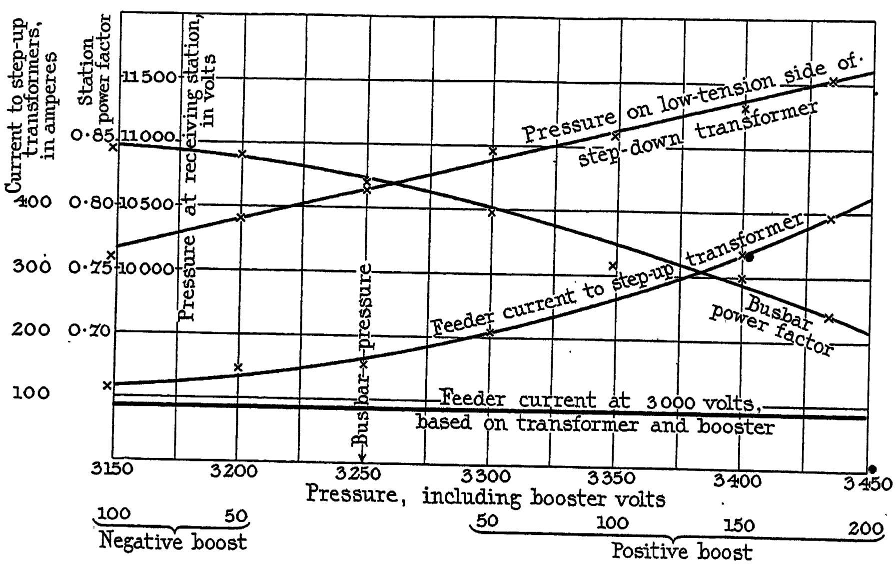


Fig. J.—Open-circuit currents, power factors and voltages on a 10-mile, 20 000-volt, three-phase, 50-period transmission line. Two 3 300-kVA, 3 000/2 000-volt step-up transformers; two 3 300-kVA, 20 000/10 000-volt step-down transformers; three single-phase boosters giving ± 6 per cent boost.

* Paper by Messrs. L. Romero and J. B. Palmer (see vol. 60, pages 287 and 803).

main load despatcher, it will be seen that, even where stations belong to the same company, trouble must ensue, and where stations belong to companies having only interchange of current arrangements the difficulties will be extremely great. Table 1 shows that under certain conditions the receiving station has to produce kilovolt-amperes corresponding to the kilowatts of its energy load at a power factor of 0·29, which would entail either abnormal generators or synchronous condensers. The authors appear to favour running this particular interconnecting line at the normal power factor of the load, with boosters to correct the busbar voltage. In all other cases, synchronous condensers would be necessary at the receiving end, as it is hardly likely that station B could deal with the enormous kVA loads at low power factors. One point which has not been considered is the question of providing the wattless kVA by large synchronous motors driving plant on the load side of station B. Under these conditions the charges for wattless energy should not be as great as those shown in Table 2, and transmission of power at unity power factor might be shown in a more favourable light. There appears to be a considerable discrepancy between the formula produced in Stone's paper * and the authors' formula for synchronizing power. Stone's formula gives the synchronizing power in kW for each degree deflection from the normal phase angle. The essential factors of the two formulæ are the same, i.e. E_1E_2X/Z^2, but the remaining factor is entirely different in the two cases. Possibly the authors could give a mathematical reason for the difference. At the same time the actual value of this factor is of small importance until a value is decided upon for the synchronizing power necessary for two power stations. Stone gives values varying from 1 to 1·5 times the capacity of the smaller plant to be paralleled. By a slight variation of this factor it appears that the two formulæ might be brought into agreement. The factor has, of course, to be varied to suit the different kinds of prime movers, as the synchronizing capacity necessary with a gas engine which occasionally misses an explosion must be very different from that in the case of a turbine with its uniform turning moment and sensitive governing gear. In our case we have a gas-engine station interconnected with several other stations and we find no difficulty in running in parallel, but we do find that there is a great tendency for the gas engine to be the first to trip out on a surge caused by a fault in any part of the system. At all times the synchronizing currents passing in this interconnecting link are large and have a definite periodicity which corresponds to the speed of the gas engines, and during periods of light load in the interconnecting link actual reversals of power take place during each revolution. Should the synchronizing power of a line at any time be found unequal to the task of keeping two stations in parallel, a simple remedy is to increase the pressure of the line, as the synchronizing power increases practically as the square of the line voltage.

Mr. I. Jones: Dealing with a few points which are met with on interconnected systems I might mention that on the system with which I am associated there are high-pressure and mixed-pressure turbo-generators, together with reciprocating low-speed gas-engine generating sets all working in parallel, and no practical difficulties are experienced in the satisfactory load adjustments of the different stations. Efficient telephonic communication is maintained between them, so that transfer of loads or other changes of running conditions can be satisfactorily arranged. In dealing with the parallel operation of the system the question of load adjustment depends, as the authors have pointed out, on the governing characteristics of the prime movers, but the question of pressure adjustment between the systems interconnected is quite a different problem, especially where the interchange of power may be in either direction and where there are large fluctuations in the load. The voltage adjustment on this system is obtained as stated in condition (3) on page 288 (vol. 60), but there are occasions when one or other of the stations has to deal momentarily with a fair amount of extra wattless current, due to varying load conditions at the consuming centres. My experience with automatic voltage regulators working with interconnected stations has not been very satisfactory, under conditions such as those mentioned above, especially in cases where they had to work as ordinary voltage regulators, but we obtained far better operation after they had been fitted with a compensating coil, being thus rendered practically power-factor regulators for the generators to which they were connected. I should like to hear the authors' experience with automatic voltage regulators on such systems. With reference to synchronizing power, I should like to know if the authors consider it necessary to have a tie line between a reciprocating or gas-engine station and a turbo-generator station of larger synchronizing power than that between two turbo-generator stations. On a number of occasions I have noticed that on the occurrence of a disturbance due to fault conditions the gas-engine generators nearly always come off the busbars first although not feeding directly into the fault. In the case of a tie line 9 miles in length connecting two of our largest power stations, at the point where it is connected with one of our main consuming centres we have no difficulty in synchronizing, speed and voltage adjustments being arranged by telephone. Have the authors met a case where it has been impossible to synchronize a tie line at some remote point on an interconnected system due to a displacement of the phase voltage?

Mr. W. Nairn: There does not seem to be much scope for interconnection between modern power stations in this country where electricity is generated from coal. Although at first sight it would appear to be very comforting to have an interconnector of large capacity between two modern power stations, yet in practice the advantage is very limited, the restricting factor being the supply of steam. Take the case of two power stations, A and B, equipped with 10 000-kW sets and with a 10 000-kW interconnector between them, and consider what happens when stati- drops 10 000 kW of load, due to a se-

* *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 1651.

out of commission. The 10 000 kW is supposed to be picked up by the interconnector and carried by station B, but what really happens is that as soon as B takes over the load the steam pressure begins to drop and B trips out the interconnector in order to safeguard the consumers in its own area. During the failure the supply undertaking finds itself in the position of having a 10 000-kW interconnector, at the one end of which is 10 000 kW of steam and no generating plant and, at the other end, 10 000 kW of generating plant and no steam. Of course it might be argued that in the event of a serious defect such as a "strip" or a "burn-out" in station A, the interconnector would be of substantial advantage, but the fact is that the money expended on the interconnector would be very much better spent in providing additional generating plant in station A. I cannot dismiss from my mind the idea that a power station is essentially an establishment for the generation and export of electrical energy and that it is no part of its business to import electricity, and I also feel that when expensive distribution cables are laid it should be into districts where there is no electricity supply and not into the heart of a generating station. From this point of view I consider the paper to be very valuable, as I believe that in some instances interconnectors have been installed without due regard to the facts which the authors have so clearly set out.

Mr. J. H. Thomas: There has been a point of apparent importance mentioned in the discussion in connection with the magnetizing current of transformers and motors as affecting the power factor. I was associated with a station generating at 3 300 volts, 50 periods, three-phase, and a number of motors wound for 3 000 volts were connected to the system. After a time the generating pressure was raised to 3 500 volts. The result was that the power factor of the station was lowered owing to the greater magnetizing current of the motors at the increased voltage. It was found that the power factor could be increased from 0·6 to 0·7 by lowering the voltage at the generating station so that the motors worked at the pressure for which they had been designed. The same point would of course apply to transformers, and this is of particular interest in the case of interconnected systems, as mentioned by the authors, who state that the voltage is widely varied. It seems to me that it would be generally a question of interconnection between systems in this country, and that under these conditions the best method of operation would be to transmit at unity power factor irrespective of the loads, and to obtain regulation by means of synchronous condensers. These can, I believe, be supplied with automatic regulators varying the excitation so as to obtain unity power factor on interconnecting lines. It is of great importance that motors and transformers should work at the pressure for which they have been designed.

Mr. D. Jenkins: Recently I met with a case very similar to that mentioned by Major David. I allude to the heavy excess currents observed by him when the voltage was increased on a line loaded only by an unloaded transformer. In my case the consumer took power at 33 000 volts through a transformer transforming down to 3 300 volts, and carrying almost exclusively an induction motor load. With the transformer secondary open the 33 000-volt circuit breaker was switched in and set to operate at about 700 kVA. The 3 300-volt switch was then closed. As soon as an attempt was made to start up a 100-h.p. slip-ring induction motor by means of a liquid starter, the high-tension switch tripped. This occurred three or four times in succession. On looking into the matter it was found that the high pressure was considerably in excess of 33 000 volts, and it was concluded that the heavy magnetizing current taken by the motor at this excess voltage was sufficient to trip the breaker. It will be noticed that the disproportion between the starting current of the induction motor under normal conditions and under these excess voltage conditions is even more extraordinary than that observed by Major David. It is true that in his case the load was an unloaded transformer, whereas in mine it was a transformer loaded only by an induction motor. Essentially, however, the load conditions are the same, in that we both have a pure induction load. Undoubtedly an excess voltage greatly increases the magnetizing current, especially if the induction plant is designed to work well up on the "knee" of the magnetization curve. No mention has been made in the paper about the interconnection of supply systems of different periodicities. At the present moment I am interested in interconnecting a 25-period and a 50-period supply. The necessary frequency changer would, when converting either way, have to run in parallel with other synchronous generating plant. I should be glad to know whether the authors have had any experience of such conditions. Is such a frequency changer a satisfactory and reliable proposition?

Mr. J. W. Fidoe: The subject of the paper is of particular interest in this district as we have a number of interlinked industrial power stations, and other interconnections are under consideration. The operation of two or more power stations in parallel has certain advantages as far as continuity of supply is concerned, but the maximum of economy would appear to be obtained where it is possible to find other undertakings having an inverse load curve, under which condition stand-by plant is reduced to a minimum. Our colliery plants carry their maximum load between 7 a.m. and 3 p.m., whereas during the remainder of the day the generators seldom carry more than $\frac{1}{3}$ load. It would be very satisfactory if we were able to sell power to local authorities for lighting and other purposes, the demand for which would be mostly after 3 p.m. For a colliery to sell power instead of coal means a change of policy, but in view of the amount of idle plant the matter is well worth consideration. The power factor of the supply is a fruitful cause of dispute, and there is evident need of a central authority to give definite orders as to the running conditions of the stations, otherwise each engineer naturally attempts to regulate his end of the line so as to carry as little as possible of the wattless current. In the examples given by the authors the overhead interconnector naturally occupies a prominent position,

but in this country we are not favourably situated either as regards climatic conditions or legal restrictions. In South Wales we have a further trouble with high-tension lines which have frequently to be carried across hilly country where they are very exposed. The south-westerly gales carry saline matter which gradually accumulates on the porcelain insulators and occasionally causes breakdowns. The use of step-up transformers is not an unmixed blessing, and where possible it is preferable to generate at a pressure high enough to render them unnecessary for the short interconnectors which are the general rule in this district.

Professor F. Bacon: I regard the paper as being most interesting and important from the points of view of both theory and practice. I, too, cannot help feeling that the magnitude and extent of the transmission systems in America make operations in this country appear comparatively trivial. One must look to such schemes as Major David mentioned, in which electrical power generated in the South Wales coalfield would be transmitted to London, to readjust the balance. Enterprise in the United States must be greatly aided by the wonderfully high overall annual load factor obtained. In this connection the table on page 297 (vol. 60) is most striking. I am sure that it would prove of general interest if the authors would explain how it is that load factors of 65 per cent and even 80 per cent are secured in America, whereas many of the biggest stations in this country have to operate at a load factor of between 20 and 30 per cent.

Messrs. L. Romero and **J. B. Palmer** (*in reply*): In reply to Major David the excessive magnetizing current, which he observed at no load and maximum boost on the line he describes, must have been due, as he says, to too high a flux density in the transformer cores, and this would not of course occur if the transformers were designed for the highest voltage to which they would be subjected in practice. It is fair to point out, however, that Major David's transformers would probably never in ordinary practice be subjected to the conditions which he mentions, as maximum boost would not be required under no-load conditions. We believe that the formula in Mr. Stone's paper gives far too high a value for the synchronizing power, although, as we have not a copy of his paper by us at present, we are unable to point out exactly where we disagree. Our own formula is worked out mathematically step by step in the Appendix to the paper, and its accuracy has not been seriously challenged.

In reply to Mr. Jones, the effect of automatic voltage regulators at the two interconnected stations is to accentuate the power factor variations of the current in the line, as the load in the line varies. If automatic regulators are not in use, the arithmetical difference between the two busbar voltages will tend to vary with variations of the load in the interconnecting line in such a way as to minimize the variations in the power factor of the line current. That is to say, automatic voltage regulators give inflexible voltage conditions under which the line power factor will depend solely on the line characteristics and load, while without such regulators the voltage conditions are somewhat more flexible. We are certainly of opinion that a larger line synchronizing power is needed between a gas-engine station aud a turbine station than between two turbine stations.

There is considerable force in the point made by Mr. Nairn as to what would probably happen if one of the generating sets in one of two interconnected stations were suddenly to go out of commission; but we would point out that if a larger number of power stations were interconnected, sufficient steam supply would probably be available to tide the system as a whole over such an accident. We are in agreement with Mr. Nairn if his contention is that the transmission of large blocks of power can only be justified when there is substantial economy to be effected by it. Recently one of the authors had occasion to investigate the question of how far from the load area it would pay to erect a projected power station in order to obtain greater generating economy by erecting it on a tidal river, the price of coal and coal-handling facilities being equal in both cases. In other words, the problem resolved itself into a comparison of the generating costs of a station having cooling towers, and one having an unlimited water supply, but with the necessity for transmitting the whole of its output. The economical distance proved to be remarkably small, as the greater efficiency of the riverside station would be offset by a comparatively small expenditure on transmission cables and the cost of supplying the transmission losses. At the same time it must not be overlooked that when dealing with existing power stations the cost of an interconnector may be amply justified by the economies incident to the improvement of the plant load factors of one or both stations, and the authors believe this to be one of the chief incentives which have brought about the interconnections already effected in this country. We would qualify Mr. Nairn's statement that a power station is essentially a plant established for the generation and export of electrical energy. In our opinion a power company or a municipality is chiefly concerned with the sale of electrical energy, and the source from which it derives the power it sells is a secondary consideration. On the assumption that an interconnection is economically sound, it would often happen that the "heart of the generating station" of the receiver system would be the only point at which the bulk supply could be efficiently received. If it were possible to interconnect through the networks of the respective systems it would obviously be advantageous to do so, but the authors' experience is that there are many cases where the only point in a network at which it is possible to receive a large block of power is the power station busbars.

Mr. Thomas, and subsequently Mr. Jenkins, refer to the variations in power factor caused by varying voltage on feeders which are not necessarily interconnectors. This is, as they suggest, caused by the saturation of the iron circuits of induction motors and transformers, and goes to show that in designing interconnections it is necessary that the effects of voltage variation should be carefully considered when deciding on the system of operation and fixing the constants of the interconnector. Mr. Thomas is probably correct in saying that the best method of operation would

be to transmit at unity power factor irrespective of the load, and to obtain regulation by means of synchronous condensers. The question is, however, one of cost and quality of service required, and can generally be decided by balancing the cost of regulating apparatus to ensure the transmission at unity power factor against the disadvantages of poor voltage regulation and cost of increased transmission losses involved by transmission at some power factor less than unity.

Mr. Fidoe refers to the economy which would be obtained if it were possible to find other undertakings having inverse load curves. In this country this condition will be the exception rather than the rule, but with colliery plants carrying their maximum loads between 7 a.m. and 3 p.m. it should be possible to effect economies by supplying energy to a power company or local authority having a heavy lighting load. We have remarked both in the paper and in the discussion at other Local Centres on the necessity for the running conditions of interconnected stations being under the control of one person, otherwise the divergent ideas of individual station operators as to the power factors and load factors at which they should operate would almost certainly result in confusion. The question of overhead versus underground transmission lines does not come within the scope of the paper, but after having seen and noted the success of overhead transmission and distribution in the United States and Canada, one cannot but feel that the overhead system has not yet been thoroughly tried out in this country.

In reply to Professor Bacon the transmission systems and interconnections in the United States are naturally on a very much larger scale than anything we have in this country, but it would be a mistake to think that our transmission and distribution systems are trivial in comparison. In our opinion the problems which have had to be faced by British undertakings, both company and municipal, are just as difficult both from the financial and technical standpoints as anything that the American companies have encountered, excepting, of course, that their operations have been on a very much larger scale than ours. It is true that the load factors obtained by the American concerns assist very considerably in the finance of the huge transmission systems which are common in America. The high load factors are brought about by a number of reasons.

The very heavy financial outlay required to construct hydro-electric plant and long transmission lines can only be justified by a load having a diversity factor which no single city could offer by itself, and this has brought into existence large power companies whose interests cover very wide areas. Many of the cities are of comparatively recent growth with no strongly entrenched competition from gas and steam in existing industrial plants. Railways are electrically operated in the United States to an extent we have only just begun to think about in England, and, as far as the Pacific States are concerned, irrigation offers a heavy off-peak load. Domestic load is most carefully fostered by the power companies and various associations formed for the purpose, and it is apparent that the propaganda which is most assiduously carried on has been very effective.

THE MEASUREMENT OF THE ELECTRIC INTENSITY OF RECEIVED RADIO SIGNALS.

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(From the National Physical Laboratory.)

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SUMMARY.

The first part of the paper is devoted to a discussion of some of the principles on which the measurement of received signals is based, and the practical application of these principles under working conditions is considered.

The latter part describes a system recently developed at the National Physical Laboratory which differs in several details from previous systems. Its operation is described in detail, and some of the possible sources of error and inaccuracy are considered.

I. PRINCIPLES AND THEIR PRACTICAL APPLICATION.

This problem is one of the most fundamental in radiotelegraphy and has received attention from large numbers of experimenters.

It is one which forces itself on everybody concerned with radio operation, as well as on those interested in the more scientific aspect of the subject. Many theories as to the cause of signal-strength variations have been suggested, and owing to the complexity of the circumstances involved it seems very unlikely that these variations will ever be expressed in a general mathematical form covering all cases; but the work of Austin has shown that, under specified conditions, a workable expression can be obtained.

For this purpose the primary need is a very large number of observations under known conditions, so that the first problem is the production of measuring apparatus the limitations of which are fairly definitely determined.

Prior to the introduction of the thermionic valve the instrumental difficulties in the way of experimenters were enormous. Beyond the small range available if direct-reading instruments were used, the only possibility of measurement was by a method involving some form of crystal detector; and, although the sensitivity of the latter is fair, the uncertainty and difficulty of calibration are a great handicap.

Such a method was indeed used by Austin * in his investigations which led up to the introduction of the Austin-Cohen coefficient; but for the longer ranges, which are the most interesting from the theoretical point of view, some more sensitive form of receiver is essential.

For measurements at very short distances a direct method is practicable. This usually consists of the insertion of a delicate thermal instrument, such as a Duddell thermo-galvanometer, into a tuned aerial or coil circuit the constants of which are known, the instrument being calibrated by direct current.

Such experiments, which have recently been considerably developed by Vallauri * and Pession,† serve a rather different purpose, their object being to determine the effective or radiation height of an aerial. For this purpose the measurements must be made at so short a distance from the aerial that the attenuation is negligible, with the result that the received signals are comparatively strong. In all cases the problem reduces to the determination of the current induced in an aerial system of known constants, from which either the potential gradient or the magnetic field at the receiving circuit can be calculated. Before the days of continuous waves the problem was further complicated by the decrement. In the resulting calculations the decrements of both the sending and receiving circuits are involved, and the determination of these alone is nearly as difficult as the original problem. With the advent of the triode with its possibilities of amplification and continuous-wave generation, the scope was very much enlarged and new methods became possible. As soon as an amplifier has to be used, however, it becomes necessary to employ some form of substitution method, because the absolute calibration of an amplifier is not at present practicable. This inevitably increases the chances of error, always very numerous, as is known by everyone who has attempted radio-frequency measurements; the result is that any method must appear to be more or less a compromise, and without extended trials and tests it is very difficult to give a decision as to which is the most satisfactory. In many cases practical considerations are of considerable weight, and from this point of view the following requirements must be borne in mind, in addition to all those of a theoretical nature :—

(*a*) The actual operation should be as rapid and simple as possible.

(*b*) Special transmission should be reduced to a minimum.

(*c*) The overall calibration should be effected as closely as possible under working conditions.

(*d*) The set should be moderately portable and capable of adaptation to varying conditions.

(*a*) and (*b*) are strictly practical questions; but they play a very important part in problems of this nature, for the case is rather different from that of a purely

* *Bulletin of the Bureau of Standards*, 1911, vol. 7, p. 295.

* *Radio Review*, 1921, vol. 2, p. 77.

† *Ibid.*, p. 228.

scientific measurement in which the whole operation is under the immediate control of the experimenter, who can repeat readings or vary his conditions as often as required. Even if the transmitting aerial be entirely devoted to the experiment its remoteness renders its detailed control difficult, and in many cases altogether impossible, with the result that the measurements must be made either on the routine transmission or on a short, special signal sent for the purpose. Observations seem to show that the first of these is not of much value except for very rough measurement, owing to the continual and irregular variations produced by the keying; and even if it be possible to obtain a reading of some sort at the receiving end, owing to these variations it is difficult to correlate it with the reading of the transmitting-aerial ammeter. If a special signal be used, working conditions demand that it should cause as little interference as possible with the ordinary routine.

This is the chief objection to a method devised by Lieut. Guierre,* in which a series of timed signals are required from the transmitting station, they being synchronized with the signals from the local oscillator. This method certainly enables various other serious difficulties to be overcome; but the organization required for an extended series of measurements on these lines would be very elaborate.

For the same reason it must be possible to obtain the readings rapidly; the set must be capable of being adjusted in working order before the commencement of the special signal, and fine adjustments must be reduced to a minimum. For instance, in the "URSI" signals the whole time available is two minutes, although the preliminary tuning-up of the set in the case of "UA" (Nantes) allows a certain margin for adjustments.

(*c*) and (*d*) are primarily questions of design, though (*d*) involves policy also. In this connection there are two alternatives. Either measurements of as high accuracy as possible may be made, involving a large amount of apparatus and a very highly skilled operator, observation points being, of course, very limited in number; or the apparatus may be in such a form as to permit of multiplication and distribution to a larger number of observers, in order to obtain simultaneous, though rather less accurate, readings. Considering the present state of our knowledge of atmospheric effects at the moment it appears that the latter method is the one from which the most useful information may be expected, and as it represents approximately the policy of the Radio Research Board, under whose direction the whole of this work is being carried out, this advantage has been borne continuously in mind.

Technical considerations.—The following methods are in use:—

(*a*) Telephone methods.
(*b*) Galvanometer methods.

Under the former heading may be included what is known as the shunted-telephone method, in which comparative results are obtained by shunting the telephones until the signal just disappears; but considerable difference of opinion exists as to the accuracy of this method,* and in any case it is not high. In all other cases the received signal is balanced, either audibly or visually, against a calibrated, local source of oscillations, from the reading of which the incoming intensity can be calculated in the required form.

* *Radio Review*, 1921, vol. 2, p. 621.

Telephones have the advantage of simplicity in use. They can be used in places where a galvanometer is impracticable or undesirable, and are familiar pieces of apparatus. Owing to their power of audible selectivity they can be used when jamming is present, though the accuracy of results obtained under such conditions requires confirmation. They also allow of the easy selection and identification of the station, and messages can be read until the last minute before taking the observation.

On the other hand, an audible method is comparatively insensitive to small variations in intensity. The author has shown * that the minimum change in intensity which can be detected under favourable conditions is about 2 per cent with spark signals. Experience tends to show that with continuous waves the figure is higher owing to the different quality of the note; and it is probable that 5 per cent is the lowest which can safely be assumed for general working. With an audible method a heterodyne is necessary, and it has also been found that telephones have a considerable effect on the amplifier. This will be referred to later.

Galvanometer methods in general involve merely the replacement of the telephones by some form of d.c. indicating instrument. The chief advantage that they afford is greater sensitivity to small variations; but it has been found from experience that they offer several other advantages, among which is the possibility of keeping the signal and its variations under continuous observation. On the other hand, the signal cannot be read directly unless an Einthoven instrument be used, and the power of audible selectivity is lost.

Fundamental formulæ.—Before proceeding to details it will be well to give the simple theory and the equations on which all substitution methods depend. Let I be the current at the base of the transmitting aerial, λ the wave-length, and d the distance from the receiving station, assuming propagation over a plane conducting surface through a perfect dielectric; then D, the vertical intensity of the electric field at the receiving station is given by:—

$$D = 120\pi \frac{Ih}{d\lambda}$$

where h is the height of the ideal Hertzian half-oscillator which would produce the same effect as the actual transmitting aerial. It is usual to call h the effective (or radiation) height of the aerial. Its value varies from about 50 per cent to 75 per cent of the actual height of the aerial, being dependent upon the form of the latter, the immediate surroundings, and also to a small extent upon the wave-length and various electrical factors. Now, if the potential gradient D be applied to an aerial of effective height h_1 and high-frequency resistance R_1, the electromotive force induced in it is Dh_1, and consequently, if the aerial be tuned, the resulting

* *Radio Review*, 1921, vol. 2, p. 282.

current is Dh_1/R_1. In the case of a coil of area a, and number of turns n, the corresponding current is

$$2\pi Da\frac{n}{R_2\lambda}$$

R_2 being the high-frequency resistance of the coil (these results are based on the assumption that the wave front is vertical, whereas experience seems to show that this is frequently not the case).* If the wave front be tilted, coil reception will be unaffected, whereas reception by means of an aerial will be changed to an extent depending on the ratio between its horizontal and vertical dimensions. If the polarization be more complex, as often occurs when night effects are present, the intensity of reception in both coil and aerial will be varied, and in such cases the intensity measured has really the value of the equivalent, plane, polarized wave, rather than that of anything possessing an actual physical existence.

The usual method of calibration is to disconnect the aerial system at intervals and to connect the receiving set to a non-radiating aerial which has the same constants as the receiving aerial and contains a calibrated mutual inductance coupled to a calibrated local oscillating circuit; the latter is then adjusted until equality of signal strength is obtained.

The applied voltage is deduced from the known constants of the local circuit; and, from the formula given above, the potential gradient is derived. This method involves the equalization of the constants of the main and dummy aerials, and the accuracy of this adjustment will be one of the chief factors determining the accuracy of the result. In addition, on switching over to the dummy aerial, any jamming previously present will disappear, thus introducing another uncertain factor into the physiological balancing process. The question of jamming by an extremely powerful station of sufficiently different wave-length to be outside the limit of audibility is one which requires experimental investigation; but it seems likely that under such circumstances, unless the characteristic curve of the receiver can be taken as a perfectly straight line, modification of the position of balance will result.

Unfortunately, with the multiplication of high-power intercontinental stations, the above is becoming a very serious factor in working on weaker signals. These difficulties are largely overcome by the method used by Lieut. Guierre, in which the ordinary aerial is used for balancing, the distant transmission being so controlled that its periods of silence synchronize with the working period of the local oscillator. The objections to this system have been referred to above.

II. The N.P.L. System.

N.P.L. apparatus.—The following apparatus has recently been constructed at the National Physical Laboratory with the object of undertaking measurements of this kind. A galvanometer method is used, the idea being to obtain greater sensitivity than is possible with telephones. In general principle it follows standard lines, but it exhibits several important modifications. Its chief features are:—

(*a*) No heterodyne required.
(*b*) No metallic screening necessary.
(*c*) Only one oscillating circuit in use at a time.

The signal from the tuned receiving circuit is applied in the usual way to a multi-valve resistance-capacity amplifier. A galvanometer is connected in the anode lead of the last valve and is made to give zero deflection for the normal anode current, a 2-volt cell and adjustable resistance across the galvanometer being used for this purpose. The incoming signal polarizes the grid of the last valve and in this way reduces its anode current, the reduction being indicated by the deflection of the galvanometer.

This is, of course, a standard method adopted by many workers. For calibration purposes the tuned receiving circuit is broken and totally disconnected from the amplifier, which is then joined to the local oscillator through a calibrated untuned coupling coil. The oscillator is next adjusted until the same deflection is obtained as with the signal.

The high-frequency resistance of the receiving circuit is also measured under actual working conditions by the movement of a switch. From this stage the calculation proceeds as before. The method differs from the normal one only in the use of an untuned circuit for calibration and in the internal design of the local oscillator; but in order to obtain reliable results great attention must be paid to a large number of small details.

General and Constructional Details.

(*A*) *The aerial system.*—The method can be applied equally well to an ordinary aerial or a closed coil. For convenience and portability a closed coil has been adopted, though this is open to several objections, chief among which are the low absorption, especially on long wave-lengths, and the antenna effect. The former is due to the fact that with a vertical potential gradient D the E.M.F. produced in an aerial is Dh, whereas with a coil it is $2\pi Dna/\lambda$. On the other hand, the directive property of a coil is often a valuable asset.

With regard to antenna effect, the behaviour of the whole coil as an aerial with respect to earth is an old and serious problem. In directional work it is one of the chief objections to the use of a plain revolving coil; but in this case one is working on the minimum of the coil E.M.F., so that the antenna effect is unmodified. In measurements where, of course, the maximum position of the coil is used, it only appears in conjunction with the coil E.M.F., but even then it requires consideration. In theory, since it flows in an untuned path it should be 90° out of phase with the true signal, provided the latter be accurately tuned. Actually, it may not be exactly 90° out of phase, and in this case it would have a component in phase with the signal. Now the characteristic feature of antenna effect in directional work is the great bluntness of the minimum, no sharp zero being discoverable. This effect can be caused only by the out-of-phase component, as the effect of the component in phase with the signal cannot be to

* T. L. Eckersley: *Radio Review*, 1920, vol. 1, p. 422.

blunt the zero but only to shift its position, since the antenna effect does not change sign as the coil passes through its zero position, whereas the coil E.M.F. does. Hence the well-known flat minimum proves that antenna effect has at least a considerable component 90° out of phase with the main signal. In the present case it can also be shown that any component in phase with the signal is small. Consider two positions of the coil 180° apart and not too near the maximum, in which case a signal of fair intensity is obtained. If the antenna effect be exactly 90° out of phase with the main signal the total E.M.F.'s in these two positions will be equal; but if the antenna effect have a component in phase with the signal the total E.M.F.'s in these two positions will not be equal, as the coil E.M.F. changes sign with the rotation through 180°, whereas the antenna E.M.F. does not. Hence the equality of the deflections at any two points 180° apart can be taken as a sign that any antenna effect present is 90° out of phase with the main signal.

To verify this, an actual test was made on the Nantes "URSI" signal. The coil was set about 30° from its maximum position, so that a fair signal was obtained, but one which at the same time would be appreciably affected by the antenna E.M.F. A reading of the galvanometer was taken, and the coil was swung rapidly through 180°, when it was found that the galvanometer reading was unaltered. Other tests seem to indicate that the value of antenna effect present on Croix d'Hins (23 450 m) is about 10 per cent of the true signal, but accurate measurement on a station is difficult, owing to keying variations; and, of course, the effect cannot be obtained from a local continuous-wave buzzer.

If the above antenna effect be 90° out of phase with the main signal, the actual signal strength will be only $\sqrt{(100^2 + 10^2)}$, i.e. 100·5 approximately, an increase of only half of 1 per cent, which can be safely neglected.

It also seems likely that the absence of an operator and telephones tends to reduce the antenna E.M.F. In this connection the following facts have been noted repeatedly.

The anode circuit of the last valve contains a double-pole throw-over switch, by means of which it can be connected either to the galvanometer or to the primary of a telephone transformer. When listening-in with the telephones it is often possible to hear, in addition to the station sought, several stations on different wave-lengths, this being effected by correct adjustment of the heterodyne only; but, on changing over to the galvanometer and re-tuning, the required signal comes in with a pure resonance curve having zeros on either side.

Also, when working on the galvanometer, the mere touching of the telephones will produce large variations in the deflection, even though the telephones are isolated from the amplifier both by a transformer and by a double-pole ebonite-insulated switch. Moreover, the amplifier often oscillates violently when the telephones are being used, whereas with the same adjustments it is quite stable on the galvanometer. The above results seem to show that if care be taken with the design and arrangement of the apparatus the effect of antenna E.M.F. is not serious.

The coil now in use consists of a wooden box frame 5 ft. square, wound with 79 turns of 7/26 S.W.G. copper wire spaced $\frac{1}{8}$ in. apart. This is sectionalized by a three-way switch so that either 29, 50, or 79 turns can be used, the coils not in use being completely cut out. With suitable condensers the range covered is from 3 000 to 25 000 m, making allowance for the fact that for work of this type it is essential that a coil should not be worked near its natural wave-length.

Probably, for the measurement of very weak signals, a coil of greater area would be advantageous, but of course it would be less portable.

(*B*) *Amplifier*.—In general this consists of a multi-valve resistance-capacity amplifier of the usual type containing, however, several special arrangements.

Resistance-capacity coupling was adopted for three reasons:—

(*a*) *Larger effective wave-length range*.—A transformer amplifier, though more efficient over a limited range, cannot be made to cover a large one without the use of interchangeable transformers; and generally it has certain points at which it is very liable to oscillate. As the set is not designed to work below 3 500 m, the question of the inefficiency on short waves of such an amplifier does not arise.

There being no heterodyne effect, audio-frequency amplification is inadmissible.

(*b*) *No screening required*.—In measurements such as these it would be essential to screen all coils and transformers thoroughly in order to avoid inductive effects from outside stations or from other parts of the circuit, as such inductive effects might be completely altered when the change-over was made from outside station to calibrating circuit.

(*c*) *Stability*.—In dealing with measurements it cannot be too strongly emphasized that the prime necessity is stability of the apparatus. Sensitivity, amplification, and even selectivity must all give place to stability. The amplifier must be kept well away from regeneration, instead of, as is usual, working as near this point as possible. Of the short time available for taking a measurement there is none to spare for fine amplifier adjustments; and, for example, a six-valve set working inefficiently, but stably, is far preferable to a "super-efficient" three-valve pattern. (A great deal of work is being done in order to get the most suitable arrangement combining fair amplification with reliable stability and ease of adjustment, the details of which are rather far from the subject matter of the present paper.)

The above three reasons have led to the selection of a resistance-capacity amplifier, though under other conditions it is possible that one of another type would be more suitable.

The chief objection to an amplifier of this type is the poor working on low wave-lengths, i.e. with small values of the tuning condenser. This is a side issue of the more important fact that every valve circuit possesses an effective impedance, which forms a load on the oscillating circuit, and so reduces its effective voltage considerably.

This has been discussed in detail by the author in another paper,* in which it is shown that if the amplifier be considered as equivalent to a high resistance R_1

* *Wireless World and Radio Review*, 1922, vol. 10, p. 351.

shunted across the condenser (this is not strictly accurate, but avoids considerable mathematical complication) the effective resistance of the equivalent simple circuit is $R + \omega^2L^2/R_1$, R being the ordinary high-frequency resistance of the circuit. Now, under ordinary conditions, with a large inductance and small condenser, ωL is large, so that it frequently happens that the first term is entirely swamped by the second; and as long as this holds, it actually pays to reduce the number of turns on the receiving coil and to increase the condenser value, since the loss of received energy due to the decreased area-turns is more than compensated for by the reduction in apparent resistance. For instance, the actual deflections of the galvanometer on a fixed signal of wave-length 9 100 m, using the three sections of the coil in turn, were of the same order; whereas the equivalent resistances were 6·5, 36 and 102 ohms, the corresponding d.c. coil resistances being 3·1, 9·0, and 12·1 ohms respectively. It appears from this that any measurement of high-frequency resistance should include the valve in working condition, especially when the ordinary circuit resistance is low.

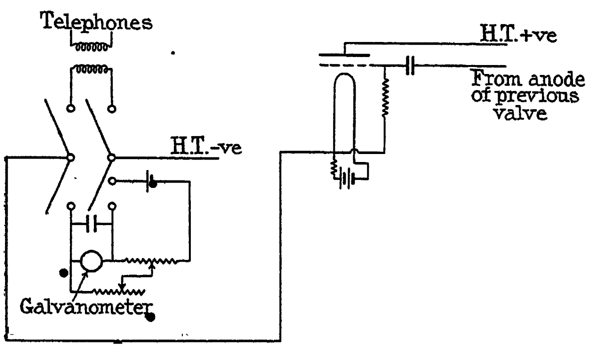

FIG. 1.—Connections of the last valve.

The special circuits in the amplifier are confined to the last valve (Fig.1). Instead of the usual telephones a sensitive galvanometer and shunt are connected in the anode circuit, and across them is placed a 2-volt accumulator with such an arrangement of resistances that the normal anode current can be balanced; the deflection is obtained by the departure from the normal, and the whole is shunted by a 5-μF condenser. Under these circumstances the effect of atmospherics appears to be small and, as a matter of fact, excellent results have been obtained during a thunderstorm.

The last valve is also run off a separate battery in order to minimize the creep of the zero due to the gradual fall of accumulator voltage on load; and for the same reason the filament resistance is a fixed one of the iron-in-hydrogen pattern. With these precautions, provided that the accumulator be in reasonably good condition, the creep of the zero is negligible except when working at the extreme limit of sensitivity of the galvanometer, a proceeding undesirable for many reasons. A double-pole throw-over switch is also provided so as to allow of the use of telephones for listening-in purposes.

In order to obtain satisfactory results with a balanced system of this type it is essential to use an accumulator and not a primary battery, and the resistances should be of a robust, stud pattern. In fact, such resistances should be used everywhere for work of this nature, as the slightly decreased elasticity, as compared with that obtained in the ordinary sliding, variable type, is more than compensated for by the increased steadiness and reliability.

Between the coil and the amplifier is the usual arrangement of tuning condenser and a throw-over switch (Fig. 2).

The latter connects the amplifier terminals either to the tuned receiving circuit or to the untuned calibrating coil, and by means of two auxiliary contacts the oscillating circuit is completely broken when the switch is in the second position. By a slight rearrangement of connections this switch can be made to introduce a dummy aerial when an audibility method is being used.

The calibrated local oscillator.—As has been mentioned above, the local source is connected to the amplifier by an untuned coupling circuit. In this way it is possible to dispense entirely with metallic screening, since there is never more than one oscillating circuit in action at a time.

Screening involves bulky and inconvenient apparatus, since the control must be either inside the screening box or brought out in a very careful manner, and the

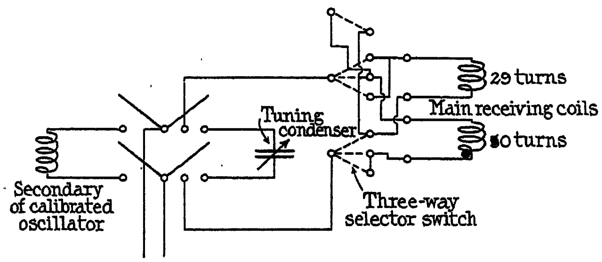

FIG. 2.—Tuning condenser and throw-over switch.

effectiveness of the operation is always open to doubt. Smith-Rose has shown * that in the immediate neighbourhood of a powerful amplifier the most elaborate screening precautions must be taken in order to ensure perfect protection, and that the difficulty increases with the wave-length.

On the other hand, this method involves the necessity of actually measuring the effective high-frequency resistance of the receiving system at each observation; but the set is so arranged that this can easily be done, and the great advantage results that a very severe check on the accuracy and correct working of the apparatus is provided.

In the ordinary systems a dummy aerial, if used, must have the same constants as the receiving system so that the high-frequency resistance problem, though latent, is still present.

Methods which introduce the calibrating oscillation into the receiving aerial avoid this difficulty, but in this case the calibration cannot be carried out until the transmitting station has stopped, whereas both "UA" and "LY" carry on with their routine work after the special signal.

* *Proceedings o the Physical Society of London*, 1922, vol. 34, p. 127.

The oscillator itself has several special features. In the ordinary construction of such oscillators a normal continuous-wave generator is used with a high-pressure supply of 50 to 60 volts, so that the oscillating current is large enough to be measured on a direct-reading instrument. A few turns of the oscillating circuit are led through the primary of a variable mutual inductance; but this arrangement involves the screening of the main part of the oscillator from the mutual inductance. Also it has been found that with the use of such comparatively high voltages there is a danger that an appreciable but indefinite amount of energy may reach the later valves of the amplifier owing to capacity coupling.

If, however, the whole of the oscillating inductance be used as the primary of the mutual, the secondary can be mounted some distance away from it, and this increase in distance and the reduction of the high-tension voltage minimize the risk of capacity coupling. This method involves actual measurement of the mutual inductance under working conditions, but this is practically essential in any case and is not difficult, whilst, with the control which will be described shortly, it is not necessary to rotate the secondary.

It is impossible to lose sight of the fact that in the normal oscillating circuit the current is not the same throughout. Prof. Howe has proved this in the case of a simple circuit; and experiments have shown that in an actual oscillator, due to the presence of the reaction coil and other apparatus, the current distribution is much modified from the theoretical form. It is therefore necessary to take a definite point on the circuit as the point of reference and to express everything in terms of the current at this point. This may involve a variation of apparent mutual inductance with wave-length; but as the mutual inductance must be determined experimentally in every case, the net result is merely to necessitate a slight wave-length correction in the apparent mutual inductance when working in the neighbourhood of the natural frequency of the oscillator.

A thermo-junction and galvanometer are connected, therefore, at any convenient point in the oscillating circuit, and all measurements are made with reference to this point. The high-tension voltage is controlled by means of a stud potentiometer so far as fine adjustments are concerned, coarse variations of the secondary E.M.F. being obtained by the use of a selector switch and a set of separate secondary coils. The instrument has been so designed that it can be fitted in a screened box for use with an audibility measurement, experiments having shown that, if the galvanometer have an iron case and be connected to the oscillator by screened leads, the leakage of oscillations is too small to cause trouble.

The secondary of the mutual inductance consists of several coils containing various numbers of turns. As the high-pressure control can be arranged to give a variation of slightly over two to one it is possible, by having several separate secondaries each containing about twice as many turns as the last, to get a very large variation of secondary E.M.F. and to retain the same percentage sensitivity on each range, the latter being an equally important advantage. The present range on 9 000 m is approximately from 5·0 mV to 0·05 mV.

Calibration of receiving set.—The formula for the results is derived as follows :—

From the second equation in Section I above we see that the current in an oscillating circuit with potential gradient D

$$= \frac{D \times 2\pi an}{R\lambda}.$$

Hence, the resonance volts on condenser, i.e. volts applied to amplifier

$$= \frac{D \times 2\pi an\sqrt{(R^2 + \omega^2 L^2)}}{R\lambda}$$

Under ordinary conditions $\sqrt{(R^2 + \omega^2 L^2)}$ may be replaced by ωL,

$$\therefore \text{ resonance volts} = \frac{2\pi anD\omega L}{R\lambda} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Since the local oscillator is then adjusted so as to give the same deflection as the incoming signal, we must have :—

Resonance volts = volts applied to amplifier by local oscillator,
$= \omega I_0 M$, where I_0 is the current in the local oscillator, and M the mutual inductance between it and the coupling coil.

$$\text{Hence} \quad \frac{2\pi anD\omega L}{R\lambda} = \omega I_0 M \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\therefore D = \frac{I_0 MR\lambda}{2\pi anL}$$

M being the appropriate value of the mutual inductance for the particular wave-length and secondary coil employed.

In connection with the local oscillator the following important point has been found. Investigations on an oscillating circuit of this form showed that the oscillating current could be expressed in the form $I = A(\lambda + B)(V + C)$, where λ is the wave-length, and V the high-tension voltage, A, B, and C being constants.

For some time this law was used to determine the current in order to avoid the use of a thermal measuring instrument, but it was found that the ageing of the valve was liable to affect the values of the constants slightly. It is quite possible that a valve could be artificially aged for this purpose, in which case a simple and rapid method of current measurement would result, but, pending the outcome of experiments to this end, a thermal instrument has been adopted. The immediate importance of the formula lies in the fact that in all cases B appears to be small compared with λ.

Hence, if $I = A(\lambda + B)(V + C)$

$$\omega IM = A(\lambda + B)(V + C)M \times 3 \times 10^8/\lambda \times 2\pi$$

i.e. the term involving λ is $(1 + B/\lambda)$

Now, for the shortest λ employed, B/λ was of the order of 0·1, so that even a 10 per cent change in the wave-length adjustment of the local oscillator only produces a change of about 1 per cent in the secondary voltage.

Hence, accurate tuning of the local, calibrated oscillator is unnecessary; it can be used to heterodyne and to read the incoming signal, and then be used without further adjustment for calibration. This effects a valuable saving of time at a period when every second is of importance.

Determination of M.—As has been mentioned above, M is not necessarily the mutual inductance measured by low-frequency methods, but the mutual inductance at working frequency referred to the current at a

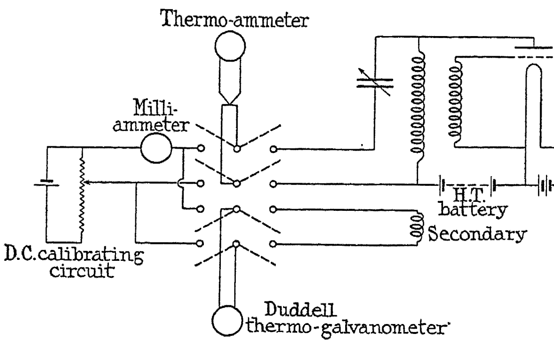

FIG. 3.—Diagram showing calibration of oscillator.

particular point on the oscillator. It is measured as follows :—

The oscillator is connected as in Fig. 3, the Duddell thermo-galvanometer with an appropriate heater being in the secondary circuit, and an ordinary thermo-junction and galvanometer in the oscillating circuit. The primary voltage must generally be higher than the usual value, in order to give a readable current in the secondary. It is assumed that on any given wave-length the current distribution in the coil is unaltered

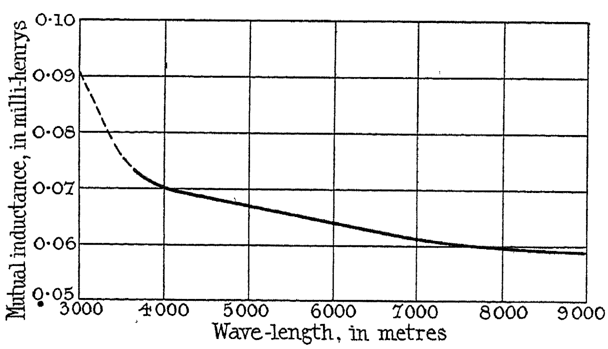

FIG. 4.—Value of mutual inductance in calibrated oscillator.

by this increase in voltage, and this seems probable as there is no grid condenser to alter the potential of the reaction coil. Also, the curve for M (Fig. 4) shows that that function has a practically constant value for the higher wave-lengths, so that the variation of distribution must be small. The resistance and impedance of the secondary are measured by ordinary methods, since its natural frequency is so high compared with those under consideration as to have no measurable effect. In addition, the secondary is of a form in which the increase of resistance with frequency is small, and as a high-resistance heater is generally required in the thermo-galvanometer this variation can be neglected.

Owing to the use of the untuned coupling it is necessary to measure the high-frequency resistance of the circuit for each observation. While this introduces an apparent complication into the process of taking a reading it has several very definite advantages, these being :—

(1) No assumptions of uncertain accuracy are made.
(2) A very severe check on the correct working of the apparatus is provided for each reading.
(3) Owing to there being no balancing circuit the number of turns on the coil can be varied at will. This is of value if it is required to take observations of stations on widely different wave-lengths with only a short interval of time between them. In addition, it is sometimes advantageous to have control of the resistance.

As before mentioned, the variable factor in each case is the amplifier itself, owing to its power absorption, and it seems likely that this property must persist even if filter circuits are used, as the power to operate the amplifier must be derived from the receiving circuit either by direct conductivity or by induction. The effect of the amplifier depends, of course, on its adjustment, and it is possible to make the loss excessively small or even negative, so obtaining regeneration.

For measurement purposes, however, either of the latter conditions is liable to produce great instability; a slight change in the strength of the incoming signal may completely alter the amplifier characteristics, and where accuracy is required it is far safer to eliminate any regenerative possibility.

In general, the more stable the amplifier the higher its power absorption, so that it is necessary to consider both of these factors; but it must be borne in mind that comparatively high power-absorption does not necessarily mean poor amplification, so that the critical factor is often not sensitivity but selectivity, which brings back the old problem of interference. The absence of a heterodyne destroys the power of audible selectivity, though the accuracy of results obtained when this power has to be exercised requires further investigation.

There is but little difficulty in reducing the total resistance of the circuit to about 10 ohms, which gives a fair degree of selectivity, and the case only becomes serious when an attempt is made to measure a weak station with a high-power station very much nearer to the place of measurement. This can be best illustrated by drawing a tuning curve.

Take, for instance, the case of "GBL" which, with 180 amperes in the aerial, at 8 350 m may be expected to give an E.M.F. of 400 μV in the coil at Teddington. Assuming the resistance of the receiving circuit to be 20 ohms and its inductance 10 500 μH, Fig. 5 gives the lower part of the tuning curve neglecting any antenna effect. It will be seen, therefore, that for a station giving an E.M.F. of 40 μV, if a measurement of the latter be required to an accuracy of even 20 per cent, the closed range of wave-length is from 7 600 m to 9 100 m approximately. Now, suppose a similar measurement to be made by the audibility method. If the heterodyne note of Leafield be just inaudible

the small station would give a good working note if its frequency differed from that of Leafield by about 3 000, i.e. if its wave-length were 9 120 m. But at this wave-length the high-frequency E.M.F. of Leafield would be 50 per cent of that of the incoming, small signal, so that unless it were certain that the amplifying power of the high-frequency side of the amplifier were unaltered by a 50 per cent increase in applied E.M.F. an error would be produced when the circuit was changed over to the calibrating source, in which no such extra E.M.F. was present.

Except under such conditions it is an advantage to use a circuit of higher resistance as the tuning is far less critical. Until a galvanometer be used one does not appreciate how critical is the tuning of a circuit of even moderately high resistance, the reason for which being, of course, the comparative insensitivity of the telephones to small changes in intensity. For instance, in Fig. 5 a variation of 10 per cent in intensity is caused

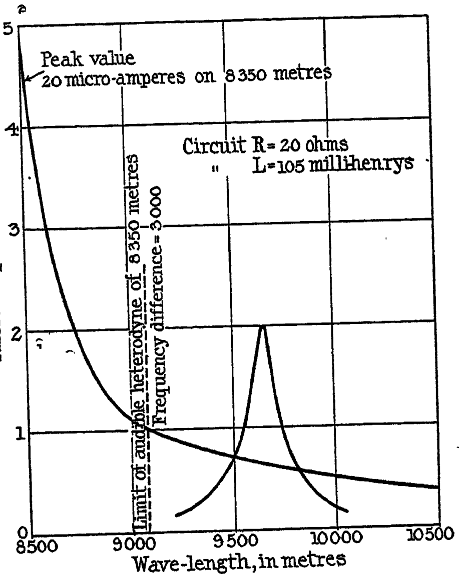

FIG. 5.—Tuning curves.

by a variation of 0·25 per cent, i.e. 4·5 $\mu\mu$F, in the capacity of the condenser. It is also important to know what error is likely to be produced if accidentally the receiving circuit be slightly out of tune with the signal under measurement. This is most likely to occur for small values of the tuning condenser where the adjustment is finer. Considering, however, the coil data given above, it can be shown by calculation that an error of 1 per cent in the condenser value, though it reduces the actual galvanometer deflection to about 45 per cent of its maximum value, only reduces the measured value for the potential gradient by 5 per cent.

The actual measurement of resistance is made as follows. The coil is fitted with a five-way switch by which resistances of 7·46, 18·3, 39·9, and 78·2 ohms can be inserted in the oscillating circuit. A signal, either from a local source or from outside, is tuned, and readings of the galvanometer are taken for all five positions of the switch. The voltages corresponding to these readings are then measured by the local, calibrating circuit, the resistance being calculated in the usual way.

From these results very important information can be obtained. Of course, if the resistance of the circuit be unusually high or exceptionally low the extreme values of the inserted resistance may not give accurate results, but the group has been so chosen as to be suitable for average working. In a particular case the following results have actually been obtained. By using the five steps and working out the results of individual pairs the following series of values for the high-frequency resistance of the circuit was found: 22·3, 22·9, 22·75, 22·35, 23·8, 23·2, 22·4, 22·3, 21·5, the average of these being 22·6 ohms; the above values are as consistent as may be expected from measurements of this nature under ordinary conditions.

Their close agreement shows the truth of the following statements:—

(*a*) The effective resistance of the amplifier is independent of the signal strength.

(*b*) Since the calculation of these results involves the figures obtained for the various mutual inductances of the secondary coils, these figures must be accurate.

(*c*) Any direct electrostatic coupling to the amplifier is negligible, since the constants in (*b*) were obtained with a thermo-galvanometer and not by means of the amplifier.

In connection with (*a*) it is interesting to note that if the amplifier be forced, this series breaks down abruptly, showing that at a certain point self-oscillation commences. Cases occur in which the values obtained with the larger resistances in series are quite normal, but an abrupt variation occurs when the added resistance is cut out. There appears some evidence in support of the idea that the amplifier resistance varies with the signal strength when close to this state.

A series of this nature is by no means exceptional, but, of course, in order to obtain such a one reasonable care must be taken to get everything into a steady state. In actual working on a definite routine it is seldom necessary to take the entire series, as a single reading is sufficient if it be known that the apparatus is working stably. It is also possible in the case of a special signal to measure the resistance by means of a local source immediately before the transmission commences. This will remain constant throughout the signal, if the duration of the latter be not too great, so that the whole time of reception can be devoted to watching and recording the momentary variations.

It appears from these results that the slight extra complication involved in measuring the resistance is more than compensated for by the very severe test applied to the apparatus in the process; and a definite indication of the accuracy of the result is obtained.

In fact, it appears from experiment that, provided the amplifier be in a stable state, its equivalent resistance on any given wave-length is definitely determined by the adjustments, filament current, high pressure, etc., and that by the measurement of these the total resistance of the coil can be foretold without actual measurement each time an observation is taken. Of course, owing

to possible slight changes in valves, and leaks, it would not be safe to dispense entirely with resistance measurement after having determined it once; but if in the course of a series of observations, through unforeseen circumstances a few measurements of resistance are missed, the values can be obtained from other readings in which the state of the amplifier was the same.

Measurements of the URSI Signals from Nantes (UA) made at the National Physical Laboratory.

Date	Potential gradient μV/m	Effective R of set	Date	Potential gradient μV/m	Effective R of set
1922		ohms	1922		ohms
Oct. 25	1 100	10·5	Dec. 1	1 670	17·7
,, 26	1 980	14·0	,, 4	3 200	20·8
,, 27	2 190	23·0	,, 6	2 310	21·0†
,, 31	1 660	16·6		2 030	
Nov. 1	2 100	9·8	,, 7	2 050	19·4
,, 2	4 260*	14·7	,, 11	1 600	21·3
,, 10	2 720	12·6	,, 12	1 800	18·0
,, 14	3 270	19·4	,, 14	1 730	21·7
,, 15	1 750	9·3	,, 18	1 650	14·8
,, 16	2 000	16·7	,, 20	1 010	10·0
,, 17	2 250	19·2	,, 21	1 360	13·0
,, 20	1 040	30·0	,, 22	2 269	15·8
,, 21	1 900	23·7	1923		
,, 22	1 795	42·5	Jan. 3	1 720	20·0
,, 27	2 440	16·0	,, 4	2 200	21·2
,, 28	1 760	16·4	,, 5	1 460	17·7
,, 29	1 420	21·4	,, 8	840	6·3
,, 30	1 950	17·6	,, 10	3 100	28·0

* Obviously an abnormal day. "MSK" (Moscow) was heard loudly on a small set on which it is normally inaudible during the day. Daylight variations of bearing were also reported as excessive.

† An abrupt change of intensity occurred in the middle of the signal.

NOTE.—These figures are the actual readings obtained and are not corrected to the standard aerial current of 180 A for purposes of comparison. The variations are in most cases not more than 2 or 3 per cent.

On the basis of the Austin-Cohen formula the theoretical value of the gradient at the N.P.L. with 180 amperes in the aerial should be 1 760 μV per metre.

Wave-length 9 000 m. Time of transmission 2.15 p.m.

In order to verify the fact that the result was independent of the particular adjustment of amplifier, a local oscillator was set up and its intensity measured. The amplifier was then considerably altered, i.e. the number of valves, high pressure, and filament current were changed, and the local source was measured again. The results differed by less than 1 per cent. The same effect has also been noticed when measuring the "URSI" signals, but, of course, in this case since 24 hours have to elapse between successive readings it is impossible to guarantee that the incoming signal remains constant to this degree of accuracy.

General observations.—The foregoing is primarily a description of the development of a system of signal-strength measurement. Time has not yet permitted of an extended series of actual observations, nor of a critical test against any other method. It is hoped to carry out both of these in the future, as until this is done it is impossible to make any very definite comparisons or to indicate which system is most suitable for any given conditions. It is also hoped to obtain useful information by the incorporation of an Einthoven string galvanometer so as to obtain photographic records of signals, which will assist in deciding another very important question, namely, within what limits of intensity and frequency an average transmission is liable to vary.

Measurement of the URSI signals from Rome (IDO) made at the National Physical Laboratory.

Date	Potential gradient μV/m	Effective R of set	Date	Potential gradient μV/m	Effective R of set
1922		ohms	1923		ohms
Dec. 12	366	22·1	Jan. 11	282	18·8
,, 13	455*	22·0	,, 15	220	12·5
,, 14	210	18·2	,, 16	383	13·6
1923			,, 18	354	12·5
Jan. 4	257	5·4	,, 19	88	2·0
,, 5	275	1·7	,, 22	270	11·3
,, 8	353	20·0	,, 23	341	13·5
,, 10	273	5·1	,, 26	277	13·2

* Poor reading.

Aerial current 100 A.

On the basis of the Austin-Cohen formula the theoretical value of the gradient at the N.P.L. is 153 μV per metre.

Wave-length 10 800 m. Time of transmission 5 p.m.

These investigations were carried out for the Radio Research Board, and the author has to acknowledge his indebtedness to the members of Sub-Committee A of this Board, detailed below, for much useful advice and criticism throughout the experiments.

Members of Sub-Committee A of the Radio Research Board.—Dr. E. H. Rayner, M.A. (*Chairman*). Admiral of the Fleet Sir Henry B. Jackson, G.C.B., M.C.V.O., F.R.S. (Chairman of the Board). Prof. G. W. O. Howe, D.Sc. Prof. E. H. Barton, D.Sc., F.R.S. Mr. D. W. Dye, B.Sc. Major J. Erskine-Murray, D.Sc. Prof. H. M. MacDonald, F.R.S. Mr. F. E. Nancarrow. Mr. J. Hollingworth, M.A., B.Sc.

Also he wishes to express his indebtedness to his assistant, Mr. H. A. Thomas, M.Sc., for his valuable aid in all the latter portion of the experimental work.

Discussion before the Wireless Section, 7 February, 1923.

Dr. J. Erskine Murray: I am very pleased to see that this type of work has advanced so far. It has been for a long time among my special interests but its extreme difficulty has always beaten me, because I have never been able to give sufficient time continuously to the subject. The author's apparatus is comparatively simple and is evidently going to do the work, and if I make one or two small criticisms it is only in the hope of suggesting slight improvements that may not have occurred to him, and in the hope that he will be able to carry the apparatus to a still further stage where it may be useful to a larger number of people. The author states that a calibrated amplifier is not possible, but I do not agree, although the present type of amplifier is for certain reasons impossible. The first is that valves are not made as accurately as engineering products; manufacturers have not yet made a valve in which the conducting elements are as exact in size and in material as, for instance, in an optical instrument. It would then be necessary to take the characteristic curves for each valve, and to have on each valve an instrument to register the emission and the anode voltage, in order to bring each valve to a definite state during use. But the first thing to do is to produce valves which will not vary if they are shaken. The fundamental formula as given by the author, $D = 120\pi$ $(Ih/d\lambda)$, has nothing to do with either the instrument or the measurement; it is merely a sort of basis for the comparison of transmission measurements. The author calls his coupling aperiodic, but this is surely not correct, because there is some capacity in the amplifier, and there is a coil connected to that capacity. It must therefore have a frequency, unless it is very highly damped. As regards screening, if a very strong signal is being measured the circuit of the local oscillator would pick up a small amount if it happened to be in the right orientation. In the calibration of thermo-ammeters by direct current, the only type of thermo-ammeter that can safely be used is a single-junction one; a multiple-junction ammeter will give very unexpected results. The reason is that the junctions are not absolutely symmetrical. The direct-current calibration of even the Duddell thermo-ammeter may differ very appreciably, e.g. 10 per cent, from that with alternating current at 300 periods or higher frequencies. It is greatly to be hoped that before long there will be a more continuous record of signal strengths, and also that it may be possible to get measurements on shorter waves. The formulæ of Fuller, Austin and one or two others give good results on comparatively long waves, say of 2 000 m and upwards, but if they were correct for short waves it would appear to be perfectly impossible for amateurs in London to hear 1 kW stations in America. There is very little doubt in my mind that these formulæ with their exponential coefficients do not cover waves down to 200 or 300 m, and it would be interesting to get some real measurements with short waves of considerable power. With short waves the consequent absence of disturbance from atmospherics would be of great advantage in the Tropics.

Admiral of the Fleet Sir Henry Jackson: In the absence of Prof. Howe, a member of the Radio Research Board, I will try to take his place and deal with the subject on their behalf. In the early days of the Radio Research Board we all came to the conclusion that some standard instrument was required for measuring the intensity of the fields at long distances from transmitting stations. Eventually the author agreed to take up the subject at the National Physical Laboratory, and this paper is the result of his work. We are, for the present, accepting the instrument as our standard, and I think that the tables shown justify us in saying that we want such an instrument. Four have been ordered: Prof. Howe is going to work one of them at Glasgow University; another one is going to Aberdeen University to be worked under Prof. MacDonald's auspices; one is going to Slough, and the fourth may be at Teddington, where one already exists at present. When these instruments are erected in the course of the next few months, we shall be able to see what difference there is between signals in the north and south of Scotland and in the south of England and possibly at some other places at the same instant. This will enable some idea to be gained as to whether the effects are local or whether they are really due to the Heaviside layer or any other cause. I hope also that it will be possible to co-ordinate direction-finding results with the measurement of these signals. It seems to me very important that if there are abnormally strong or weak signals, and the directional effects are peculiar, it would be worth while analysing the two together. With two stations, such as Slough and Teddington, in telephonic communication, we might be able to measure the two effects simultaneously and see if the bearing errors varied at the same time as the abnormal strength of signals on this instrument. The author mentions the fact that these electric waves may sometimes not arrive absolutely vertical on the antenna. In some work which I have been doing for the past two years I have tried to measure this inclination, if any, by means of a frame aerial which I can rotate in any plane. About a year ago I described some work which I had done with a frame aerial working on two axes, and I have now one which works on three axes. I have taken every precaution which has been suggested to me in discussions at the various Sub-Committees of the Radio Research Board, and I have obtained some interesting results. It is sometimes possible to put the axes at such angles that a rotation on one of them will not change the strength of the signal, and a blind band, a degree wide, will be obtained. The maximum deflection from the vertical that I have measured is about 20 degrees. I hope that others will carry out this sort of work and take measurements to observe if the waves are inclined. I have often noticed what may be called "wireless fogs." In one case at sunset I was observing a station and tuned to a 600 m wave, and I could get practically no directional effect at all for some minutes, but 20 minutes after sunset the bearing could be accurately measured. At other times the direction

of near stations could be accurately taken, when distant stations gave no directional effect at all. These points may be of interest, and I hope that they will be considered in connection with the future measurement of signal strength.

Dr. E. H. Rayner: The work described has been carried out under very great disadvantages. The fact that only a few minutes a day have been available for making experiments, and never more than two minutes together, is sufficient to show what patience is required in work of this nature. It is to be hoped that there will be a considerable increase in the number of URSI signals and in their duration. Comments and suggestions will be most warmly welcomed by the Sub-Committee of the Radio Research Board which has to deal with this subject. The Committee make no claim for credit for the work which has been done by the author, and on their behalf, as Chairman of the Committee, it is a great pleasure to me to offer him their thanks and congratulations. The further work on these lines when we have a number of stations working, combined with simultaneous observations of the direction of the apparent wave-front, cannot fail to give results of the greatest value, especially on "disturbed" days.

Mr. E. B. Moullin: Every detail of this paper has been of peculiar interest to me, for the author and I have been working quite independently at the same problem during about the same period of time. I think that anyone who has used both the audible and the visual method of comparison, as both the author and I have done, must be convinced of the great superiority of the visual method. I think that, except in very special cases, the audible method is a thing of the past. The author's reference to the difficulty of adjusting to perfect resonance even in comparatively high-resistance circuits seems very familiar to me. I think that perhaps the difficulties in preparing the apparatus have made him slightly exaggerate the necessity of making measurements with great rapidity. Surely signal measurements are of great commercial importance, and if this is so the necessity merits plenty of special signals, and the serious experimentalist should not have to put up with the best that chance gives him. Large sums of money are being spent on erecting stations of ever-increasing power so as to ensure continuous service. This has proved a successful though expensive method, but now that signal measurements can be made with a visual indicator, with certainty and comparative ease I think that the solution of questions such as optimum wave-length for a given distance, the relation between wave-length and fading and wave-length and atmospherics, has become an economic necessity. If special signals are arranged during an interval of, rather than before, regular service three or four long dashes of half-minute duration should be ample; the general disturbance caused thereby would be small. I am surprised that the author considers that reception with a loop is advisable, for it greatly enhances the difficulties. If an aerial is used, the E.M.F. set up by a given field strength will be vastly greater than that in a loop, and consequently the necessary number of amplification stages can be much reduced, with a great gain in ease of manipulation. It may be argued that the aerial has to be calibrated, but this can be done by measuring a strong signal both in the aerial and in a loop. Also, if signal measurements are required for investigating fading effects and the like, is it not relative rather than absolute values that are required? I think that there is a good deal to be said for replacing the loop by a big aerial. Now if the E.M.F. to be measured is fairly large and the number of amplifier stages are few, I do not find that screening is a very difficult matter. As the author's method requires a local generator to calibrate the amplifier, is there not something to be said for introducing the local E.M.F. straight into the aerial circuit rather than working indirectly via the aerial resistance? The author tells us that he does this to avoid screening, but if aerials are used instead of loops is there any point in avoiding screening? With audible comparison I think there is, because, as the author says, there is always the uncomfortable feeling that perhaps the screening is not complete. With visual indication, on the other hand, this doubt need not exist. The current in the local generator being kept constant, the E.M.F. introduced into the aerial may be varied by altering the value of a mutual inductance or of a resistance potentiometer. If the screening is imperfect the E.M.F. introduced through stray paths will remain constant, while the E.M.F. that it is desired to introduce will vary. The galvanometer deflection can be plotted against the value of the mutual inductance, and if the result is a straight line through the origin, the screening is shown to be perfect. If it is not perfect then the screening can be improved until the calibration line does go through the origin. I have used this method of measurement* and find it to be comparatively simple. I should like to know the author's views in regard to the use of aerials and with regard to introducing the E.M.F. directly in the aerial. Does he consider that there is some distinct advantage in working via the aerial resistance?

Major H. P. T. Lefroy: On page 505 the author lays emphasis on the necessity for using an accumulator for balancing, but he does not state what type of high-tension battery he employs. If it is an accumulator battery I can see his point, but if it is a dry-cell battery would he not get as good results by using, for balancing, one cell of the same type? As the currents are balanced to zero, it follows that both batteries discharge at the same rate, and so the more uniform they are in construction the steadier should be the zero. On page 504 the author mentions that he has $\frac{1}{8}$ inch between the turns of his coil-aerial, but this apparently does not come into his calculations, unless it is covered by his measurement of the effective resistance of the coil aerial. I am doubtful whether, in the case of absolute measurements, it is safe to ignore the distance between the turns of such a coil aerial. It is my experience that, for a given area and number of turns, the wider the spacing of such turns the stronger are the signals received. I presume that this means that the voltage on the detector is greater the wider the spacing of the turns. It seems probable that the nearer the coil turns are, the more they tend to screen each other from the incoming signals. I am doubtful whether this

* See *Journal I.E.E.*, 1923, vol. 61, p. 67.

effect is completely allowed for by measuring the effective resistance; would it be just as good for the author's purpose to have, for instance, $\frac{1}{16}$ inch between turns? On page 509 the author refers to the special conditions that existed on the 2nd February, 1922, and I should like to ask him whether he made a point of recording the meteorological conditions on that day? From the nature of his investigations he is in a position to observe frequently the abnormal strength or weakness of standard signals, and a careful analysis of the corresponding meteorological reports might lead to some insight into what weather conditions accompany abnormal signal strengths. I have evolved a rough method for the measurement of signal strength, which may be described as a zero method. The receiver is first balanced to zero for silence; when the signal arrives a certain deflection occurs; by adjustment of the filament rheostat, whilst the signal continues, this deflection is again balanced to zero; the rheostat is arranged to have an open scale and a suitable pointer, and the change in its value between the two positions of balance indicates roughly the strength of signal received. The change is usually about $\frac{1}{2}$ ohm to $\frac{3}{4}$ ohm, and the balances can be easily and rapidly obtained.

Mr. T. L. Eckersley: The value of the paper is enhanced perhaps because, it seems to me, the author has developed an instrument which differs in important respects from the ones that have been in use up to the present, i.e. the method due to Vallauri and that developed in the Marconi Company by Capt. Round, Mr. F. C. Lunnon, Mr. K. W. Tremellen and myself. A comparison between his apparatus and our own should give a valuable check on the accuracy of the overall working of each type of instrument. The chief novelty of the N.P.L. system is in the use of a galvanometer for matching the actual and local signal, and very strong opinions have been expressed during the discussion that this is the only reliable or even possible method, and, although I fully recognize the insensitivity of the aural method of matching signals, the galvanometer method has the serious disadvantage that it cannot be used on ordinary Morse signals. I should like to know whether the author has been able to measure with the galvanometer weak signals from the American stations, e.g. down to 4 or 5 microvolts per metre on wave-lengths between 10 and 20 km. With regard to the accuracy of matching audio signals I agree with the author that 5 per cent is about the limit of accuracy in normal working, but in exceptional cases where strong signals are used, interpolated by signals from the artificial circuit, an accuracy of 1 per cent has been obtained by Mr. Lunnon when comparing two signal-measuring instruments. I am inclined to feel that the gain in accuracy on using a galvanometer is outweighed by the disadvantage consequent on loss of audio selectivity and the impossibility of use on ordinary Morse signals. I should also be inclined to think that the galvanometer method would fail in the presence of strong X's where it is still possible to match audio signals with a fair degree of accuracy. The author's method also involves the measurement of the resistance of the receiving aerial. Personally I have always found this to be a difficult matter and one that is always liable to some uncertainty unless very special precautions are taken. Again, the mutual inductance must be measured. All these measurements—made against time—appear to me to introduce possibilities of error which the direct substitution method avoids. It has been our practice for some time past to do away entirely with the dummy circuit and induce the local signal direct into the aerial during the intervals of sending. The actual and local signals are then under the same conditions of X's and jamming, and can be matched without any fear of the psychological effects of X's marring the results. I can vouch for the fact that this method is possible, as I have received many thousands of observations from Mr. Tremellen taken in this manner on his voyage out to New Zealand. This method avoids all uncertainties of resistance measurements. It is sometimes difficult to find intervals to "chip in" when a station is sending high-speed automatic signals for long periods, but in this case it is possible to use a method devised by Mr. Beverage and Mr. Rust in which a unidirectional receiver is used, by combining vertical and aerial and frame, in which the intervals are artificially made by balancing the frame against the aerial. On page 503 it is not fair to say that if the wave be tilted the relation $I = 2\pi Dan/(R_2\lambda)$, where D is the vertical force induced, holds, for the E.M.F. induced in this case also depends on the horizontal electric force X in the direction of propagation and is $na \cdot \partial X/\partial Z$. This quantity is, however, negligible in every case where the ground has not a greater resistivity than about 1 000 ohms per ft. cube, or about 2×10^{13} units. With regard to the effect of jamming, it has been our experience, so far, that when using our types of measuring instruments, jamming makes very little if any effect on the measured strength of the signal received. The use of a strong local heterodyne makes the signal and the interference very approximately linearly independent, but I should doubt if this was the case when using ordinary rectification without heterodyne. This raises the point as to whether the absence of a local heterodyne is really an advantage. It certainly is an advantage in simplicity, but the point raised just now may be serious in certain cases, and ordinary square-law rectification makes weak signals difficult to measure. The author must be congratulated on being able to dispense with shielding, although his method of doing so is not exactly clear to me. It seems to me rather a dangerous proceeding, especially when dealing with very weak signals. The capacity coupling with a resistance amplifier is likely to be of the same order of magnitude as the inductive coupling, so that the use of a resistance-capacity amplifier cannot facilitate to any great extent the problem of shielding. The fact that the local oscillator may be slightly mistuned without altering the effective E.M.F. induced in the amplifier seems to be a point in the favour of the N.P.L. system. With the use of a heterodyne very accurate setting of the local oscillator is necessary in order to match the heterodyne notes. This setting is often made more difficult by slight variations of the signal wave-length, and generally involves considerable care and time in adjustment.

Mr. F. J. Chambers: With reference to the need for a stable amplifier, I should like to ask the author if he has tried substituting well-insulated condensers for the grid-filament resistances. The reaction of the output circuits upon the input circuits, due to "valve" coupling, is then "counter feed back" and can be reduced to a negligible value by making the condensers large compared with the anode-grid capacity of the valve. The principal source of trouble in a resistance amplifier is the action at the first stage. This might be dealt with by connecting the source of E.M.F. to the first grid through a non-inductive resistance, with a further non-inductive resistance between the grid and filament of the first valve. If these resistances are properly chosen with reference to the other circuit constants, the anode reactance and the grid-anode capacity, I think that retro-action could be avoided.

Mr. E. H. Shaughnessy: On page 502 the author points out that the measurement of signals can be made either on the routine transmission or on a short, special signal sent for the purpose. He says: "Observations seem to show that the first of these is not of much value except for very rough measurement, owing to the continual and irregular variations produced by the keying." I should like to know precisely what he means by that; whether it is simply the fact that his galvanometer needle vibrates too much for him to get a reading, or whether the strength of the field when signals are coming in differs appreciably from that when a long dash is being sent. From a practical point of view we want to get signals and not long dashes. That is why up to the present the audibility method has been used for measurement, and, following the Marconi practice, we have always applied it to actual signals. The table on page 509 shows that the strength of the field as measured varies from 1 040 on 20th November to 2 250 on 17th November and 1 900 on 21st November. I am ignoring the abnormal figures, and I presume that these measurements were taken at the same time every day. An engineer designing a station is very badly in need of some substantial and accurate figures of this nature. The strength of the signals on one day was 4 260, and someone may accept this as reliable, whereas the figure that should be taken is that for 8th January, viz. 840. Measurements taken all over the world with apparatus of this or a similar nature will be very valuable to us all.

Professor E. W. Marchant (*communicated*): In a paper read before the Institution in February, 1915, (see *Journal I.E.E.*, vol. 53, p. 329) I described a method of measuring the signal strength which had been used in the Liverpool Laboratories of Applied Electricity for determining the variation in the strength of the Paris time signals and of a station at Brussels. In these tests we used an Einthoven galvanometer in conjunction with a crystal (perikon) detector which was calibrated by a buzzer circuit, the current being measured by a Duddell thermo-ammeter. These measurements were mainly relative, the absolute values of the microvolts per metre on the aerial not being estimated. The aerial was very badly placed for this purpose as it was attached to a mast erected on the top of a steel-frame building, and its effective height, therefore, would be difficult to determine with any degree of certainty. Since last September, Mr. Sharpe in this laboratory has been constructing an apparatus for measuring signal strengths of much longer wave-length, the arrangement used being somewhat similar to that described by Mr. Lunnon in the discussion some two years ago on Mr. Elwell's paper on "Long-Distance Wireless Transmission."* The arrangement described in the present paper, also, is somewhat similar to our system, the galvanometer being connected in the plate circuit of the last valve, a balance current, obtained from a secondary cell, compensating for the steady current which flows through the plate circuit, so that the galvanometer only records variations in the plate current, corresponding to the received signals. So far, no actual measurements have been obtained of the long-distant stations. The greatest difficulty in connection with these tests has been the elimination of signals of similar wave-length to those being measured. The method of calibrating the detector described by the author is very similar to that which we used in our tests in 1914, but the variations in signal strength that the author has obtained and described on page 509 are much greater than those found in most of our experiments for the daytime. The actual variation during the day for the Paris time signals in Liverpool (which would be roughly the same distance as Nantes is from the N.P.L.) is of the average order of ± 25 per cent, depending on weather conditions. Variations during the night are, of course, very much greater and I presume that the figures given on page 509 for the signals from Nantes (UA) must include some measurements after dark. The variation in the effective resistance of his testing set appears to be very considerable, having a minimum value of 6·3 and a maximum of over 42. It is difficult to understand exactly why it is necessary for the receiving set to have such a very wide variation of effective resistance. Would it not be better to use for receiving a set in which the effective resistance was practically constant? Reference is made on page 508 to the variation in sensibility of the author's receiver with varying high-frequency E.M.F. of the received signal. Unless one is going definitely beyond the saturation point of the valve with any of the signals, there should not be any serious change of sensitivity with varying E.M.F. of the received signal. It is, I think, desirable to work the amplifying valve as near as possible to the centre of the straight part of the characteristic curve, so as to make sure that this condition does not occur.

Mr. J. E. Taylor (*communicated*): Some 11 or 12 years ago I had some preliminary tests made with a view to measurements of wave-strengths at a distance from the transmitting station. At that date damped-wave transmission from spark transmitters was in general use and the tests were confined to such transmission and to relatively short waves not far removed from the natural wave-length of the aerial used and of perhaps 200 m to 400 m. The distance from the transmitting station at which the measurements were made was also quite small, i.e. about two or three miles. The method consisted of inserting a Duddell thermo-galvanometer into a receiving aerial, and an attempt

* *Journal I.E.E.*, 1921, vol. 59, p. 677.

was made to obtain a resonance curve from the galvanometer readings while varying the tuning of the receiver through a suitable range. It had been expected that the curve so obtained would bear some direct relation to the resonance curves obtained at the transmitting station by the usual method of wave-meter and thermo-milliammeter. On the contrary, however, the curves at the receiving station had entirely different characteristics and indicated a bluntness of tuning not accountable for by the measured effective resistance of the receiving system. They also exhibited a double-hump characteristic in which the humps bore no sort of relation to the coupling waves of the transmitter. The bluntness of tuning was such as to swamp entirely any characteristics of the transmitter, the coupling waves of which might be varied within wide limits without being detectable. It was also confirmed that with ordinary wireless crystal receivers the coupling waves were undetectable, so that the necessity for legislation as regarded the permissible limits of coupling of transmitters was not obvious. Such legislation appears to have been based on erroneous assumptions derived from resonance curves taken at the transmitting station itself. Probably somewhat similar tests have been since carried out by other investigators and have been carried to a more definite conclusion than the incomplete series to which I refer. Bearing in mind the nature of the results obtained with damped-wave transmission as above, I should like to know if the author has evolved any resonance curves with his apparatus on continuous-wave reception and, if so, whether he has found that they bear any direct relation to resonance curves obtained at the transmitting station. If he has not yet made such tests I think it would be time well spent to do so. The author's method, systematically pursued, promises results of great interest, more especially in regard to comparative results as between different types and locations of stations, as well as seasonal and other variations of signal strength.

Mr. J. Hollingworth (*in reply*): I quite agree with Dr. Erskine-Murray that the problem of a calibrated amplifier is one of apparatus rather than of principle, and it is quite likely that with improvements in valve construction such a thing will become possible, though it seems likely that even then the adjustments might be highly critical. In accordance with his suggestions the word "aperiodic" has been changed to "untuned." As to "pick-up" in the local oscillator, if it were suspected, it could be eliminated by slightly changing the wave-length, as it has been shown that such small changes do not affect the calibration. There is no doubt a great field in the extension of such measurements to short waves and it is hoped to carry it out, but with the reduction in wave-length the instrumental difficulties increase very rapidly owing to the increased effect of small stray capacities at the higher frequencies.

It is hoped that further tests may justify the use of the apparatus as a standard as suggested by Admiral Sir Henry Jackson, but on work of this nature it is important to define what is meant by this expression. In ordinary electrical measurements no instrument can lay claim to be called a standard unless it can be relied on to an accuracy of at least one in a thousand. In the present state of radio work of this nature such an achievement is, of course, impossible; and the word must be taken as implying that the limits of accuracy are definitely defined in each case. The check involved by the resistance measurement appears to provide this, and gives a power of separating good and bad readings whether such are due to the set itself or to transmission irregularities. During the Horsea tests last year some experiments were made to see if there was any direct connection between abnormal bearings and abnormal signal strength. The results, considering individual observations, appeared to be entirely negative, but from results such as that on 2nd November it appears that a period of abnormal signal strength may be accompanied by directional variations, even if the converse is not true. When the station at Slough starts working regularly such simultaneous observations would be possible and certainly of value.

The problem of aerial versus coil raised by Mr. Moullin is one in which there is a great deal to be said on both sides. The fundamental advantage of the aerial is certainly the large E.M.F. and, consequently, the decreased amplification involved. The primary reasons for the use of a coil in these experiments were portability and possibility of use in places where an aerial was impracticable; also the coil has the advantage that its constants are much more definitely known than those of an aerial. For pure comparative purposes this does not matter, but it affects any attempt to obtain absolute figures. The determination of the effective height of an aerial is one on which there is much uncertainty at the present;* and Vallauri has shown † that it may vary very considerably with the orientation of the observing station. It also varies with the wave-length, and possibly with the surface conductivity of the ground in the neighbourhood. The method of injecting the calibrating E.M.F. into the aerial is practically that of Lieut. Guierre and is discussed on page 502 of the paper, the whole problem being the difficulty of ensuring a silence period in which to perform the injection.

In reply to Major Lefroy the high-tension battery consists of small Leclanché wet cells. So far this has given no trouble, though admittedly it is fairly new. The steadiness of the anode current (i.e. the filament emission) depends on two factors, the anode voltage and the filament temperature. If the valve be run very bright on the upper flat portion of the temperature/emission characteristic, the latter of these two factors is negligible and the problem is merely a question of steadiness of anode voltage. For efficient working it is usual to run the filament less bright on the steep part of the characteristic, and in this case a much greater variation of anode current is caused by small variations of filament voltage than by corresponding small variations of anode voltage. In this case it has been found best to balance the filament drop by an accumulator working on a potentiometer of about the same resistance as the filament.

* Eckersley: *Electrician*, 1923, vol. 90, p. 134.
† *Radio Review*, 1921, vol. 2, p. 186.

The question of spacing is a very interesting one. It is equivalent to the consideration of the screening effect of the current in any turn on adjacent turns. Now the occurrence of such an effect is illustrated by the fact that if the wire resistance of a coil were decreased indefinitely the current in it would tend to a finite limit. This is shown in the theoretical treatment of the coil by the appearance of a quantity known as the radiation resistance, which depends on the dimensions of the coil and is added to the normal wire resistance. It appears, therefore, that any such effect is allowed for by the measurement of the resistance under working conditions. Actually the radiation resistance of a coil is usually very small compared with its wire resistance. A more likely reason for the effect referred to by Major Lefroy is that as the spacing between the turns is decreased the inductance rises fairly rapidly. Now I have mentioned on page 505 that if there be any power absorption by the valve, or loss due to poor insulation resistance, the effective resistance due to this is nearly proportional to the square of the inductance. It seems more likely that the behaviour referred to was due to this cause than to the one previously discussed. There is also the fact that the actual high-frequency resistance of the wire composing the coil itself is affected by the spacing. I think that there is no doubt that the meteorological conditions play a considerable part in the variations, although I have not actually confirmed it in the case of 2nd November, but it is an effect I have frequently suspected from the results obtained. It will certainly be taken into consideration as soon as systematic observations begin. As to the earlier remarks of Mr. Eckersley, I agree that it is too early to give a definite decision as to the relative values of galvanometer and telephone methods, though there appears to be a general tendency among the more recent workers to use the galvanometer. Personally I am inclined to think that, owing to the large number of different conditions under which such measurements are required, there is room for both types.

One object of signal strength measurements, and indeed a very important one, is the determination of their value under actual routine conditions of working. These are not invalidated by such factors as excessively weak signals, bad atmospherics and unsteady transmission, which factors must be allowed for in considering such transmissions, and even if the results obtained are not of a very high order of accuracy their value is considerable. For such work an audibility measurement is probably most suitable. The N.P.L. apparatus was, on the other hand, designed more for theoretical observations on the "URSI" signals. In this case the limits of accuracy of each individual observation must be known and must be correlated with carefully observed sending conditions. Observations on the dashes seem to suggest that a transmitting set does not always settle down immediately to a steady condition when the key is pressed, and in this case it is not easy to specify the exact transmitting conditions when Morse signals are being sent. This also covers the point raised by Mr. Shaughnessy. The consistency of the resistance series obtained seems to show that, for a coil at any rate, it is a fairly definite quantity, though with an aerial it might not be so. The mutual inductance has not to be measured during the observation, as it is determined once and for all during the preliminary calibration of the apparatus. This and the fact that accurate tuning of the local oscillator is unnecessary make the actual measurement very rapid. Readings have been obtained with time to spare in cases when no preliminary signals were sent, but merely the URSI call immediately followed by the dash. I think that the abolition of the dummy aerial in Mr. Eckersley's system is a very great improvement, though it is only obtained rather at the expense of simplicity of apparatus. I do not quite follow his remarks as to capacity coupling, as he does not say between what points he is considering it; the primary reason for there being no need of screening is that the coil and local oscillator are never working at the same time. The capacity component of the calibrated mutual inductance is allowed for by the method of calibration, and stray capacities between the oscillator and amplifier are minimized by mounting everything on porcelain legs. It was found by experiment that the ratios of the mutual inductances of the various secondary coils as measured by the method given in Fig. 3 agreed generally within 1 per cent with the same ratios obtained by varying the current in the calibrated oscillator so as to give the same galvanometer deflection on the amplifier with different pairs of secondary coils. As the amplifier is not used at all in the first method this shows that the effect of such stray capacities is negligible.

I have not tried the method suggested by Mr. Chambers, but any method of controlling rather than abolishing retro-action is to be welcomed.

The variations in resistance referred to by Prof. Marchant are due to three causes. The first, which in general accounts for the slight variations, is due to slight changes in the batteries, etc., and also at times to dust or damp on the leaks. The amplifier used for these measurements was the original model constructed in the early days of the experiments. Many modifications and improvements are being incorporated in the later model which is now under construction. The two other causes were intentional. The first of these was that the amplifier adjustments were varied so as always to give a practically full-scale deflection on the galvanometer. For instance, in a case where the signal was larger than usual and the galvanometer under normal conditions just off the scale it gave a finer adjustment to vary the amplifier slightly than to use the galvanometer shunt of which successive steps were in the ratio 3 : 1. The extreme variations were due to another cause. As in this method of measurement the state of the amplifier is directly involved in the calculations, it was thought to be of the utmost importance to show that this did not affect the final result. The amplifier was therefore varied by using two, three or five valves and widely varying amplifications on different occasions. This is strongly illustrated in the reading on Rome on 5th January where the amplifier was deliberately

made almost reactive, its resistance being only 1·7 ohms; and yet the reading was still consistent with others, whereas the amplification was many times greater. The readings on Nantes were all taken at 2.15 p.m. (G.M.T.), this being the time of the special signal. The variations are certainly large, but appear in general to be of the same order as those observed at Meudon on similar transmissions.

In reply to Mr. Taylor I have not been able to determine any resonance curves such as he refers to, but this could easily be done when the transmission from Teddington to Slough is in working order.

PERMISSIBLE CURRENT LOADING OF BRITISH STANDARD IMPREGNATED PAPER-INSULATED ELECTRIC CABLES.

SECOND REPORT* ON THE RESEARCH ON THE HEATING OF BURIED CABLES.

[REPORT OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION, PRESENTED BY MR. S. W. MELSOM (NATIONAL PHYSICAL LABORATORY), ASSOCIATE MEMBER, AND MR. E. FAWSSETT, MEMBER.]

(*Read before* THE INSTITUTION 1*st March, before the* NORTH-EASTERN CENTRE 12*th March, before the* NORTH MIDLAND CENTRE 20*th March, before the* NORTH-WESTERN CENTRE 20*th March, and before the* SOUTH MIDLAND CENTRE 4*th April*, 1923.)

CONTENTS.

* See *Journal I.E.E.*, 1921, vol. 59, p. 181.

Theoretical and experimental work—*continued.*

Synopsis.

This Report describes the further investigations on the Heating of Buried Cables and includes the essential portions of the Preliminary Report (*Journal I.E.E.*, 1921, vol. 59, p. 181).

The theoretical and experimental work has been carried to a stage at which it is possible to issue tables of maximum permissible currents for all the sizes and types in general use of paper-insulated cables dealt with in the British Standard Specification for Dimensions of Insulated Annealed Copper Conductors for Electric Power and Light (B.S.S. No. 7—1922).

Tables of maximum permissible currents (page 521).—Tables of maximum permissible currents for all the sizes and types in general use of impregnated-paper lead-covered cables dealt with in B.S.S. No. 7—1922, have been calculated on the basis of experimental results obtained with a large series of cables, both with circular and segmental conductors and including both armoured cables laid direct in the ground and lead-covered cables in ducts.

Full notes are given with the tables, explaining the method and bases of calculation, and an indication of the effects of variations from the assumed constants.

Constants employed (page 534).—The constants recommended and on which these tables are based are as follows, the reasons for making this selection being given later:—

(1) Thermal resistivity of the dielectric (page 534):
For cables up to and including 2 200 volts = 750.
For cables above 2 200 up to and including 11 000 volts = 550.

Higher values have been adopted for cables with conductors having sectional areas less than 0·06 sq. in. to allow for the difficulty in manufacturing small cables.

(2) Thermal resistivity of armouring and protective coverings (page 524) = 300.
(3) Thermal resistivity of the soil (page 535).

Current-loading tables are given corresponding to the following values of thermal resistivity and moisture content:—

Thermal Resistivity, g	Approximate Moisture Content	
	Sandy Loam	Heavy Clay
340	0	1 %
180	5 %	17·%
120	10 %	—
90	15 %	—

In the case of heavy clay soil with moisture content greater than that given above the value of the thermal resistivity is not reduced appreciably; for instance, with a moisture content of 25 per cent the thermal resistivity is approximately 150 (see Fig. 5).

(4) Depth of laying (page 538).

As representing average practice the depth of laying is taken as 18 in. to the cable axis for cables for pressures up to and including 2 200 volts, and 3 ft. for cables for pressures above 2 200 volts up to and including 11 000 volts.

(5) Temperature limits (page 541).

The normal maximum temperature of the soil is taken as 15° C.

The maximum temperature to which the dielectric and conductor may be exposed is taken as 65° C. for armoured cables laid direct in the ground, and 50° C. for plain lead-sheathed cables drawn into ducts.

The temperature-rises on which the tables are based are therefore 50 degrees C. and 35 degrees C. respectively.

Theoretical and experimental work (page 533).—The report and appendixes together give a detailed account of the problems underlying the investigation and the experimental work necessary for their elucidation. These may be briefly summarized here.

The evaluation of the temperature-rise of the conductor of a cable buried in the ground depends on the fundamental relation

$$H = t/(S + G)$$

where H = heat developed in the conductor per sec.
t = temperature-rise of the conductor.
S = thermal resistance between the conductor and the surface of the cable.
G = thermal resistance of the ground surrounding the cable.

The consideration in detail of the separate terms of this equation is a convenient way of reviewing the main outlines of the problem.

The heat per sec. H depends on the current and the resistance of the conductor or conductors. In the report it is expressed in watts. The introduction of any conversion factor in the equation is thus obviated, as the thermal resistances and resistivities are also expressed in electrical measure (i.e. the difference in degrees C. which causes the transference of one watt, or one joule per second, of heat).

The dielectric loss is neglected as it is negligible within the limits of 65° C. and 11 000 volts.

The temperature-rise t of the conductor is an arbitrary value which has been adopted as the result of existing data.

Existing information as to the temperature to which cables can be subjected for long continued periods without injury is most conflicting, and the experimental work necessary to provide reliable values is not complete and will necessarily require a considerable time. All published results have been fully examined, as have also other factors such as the expansion and consequent mechanical strains on cables subjected to alternate heating and cooling, and after full consideration of all sides of the question, including the reliability expected with underground mains, values of a maximum permissible conductor temperature of 65° C. for armoured cables laid direct in the ground, and 50° C. for plain lead-sheathed cables drawn into ducts were adopted.

A large amount of data has been collected for Great Britain and other countries, including India and Australia, of the temperature of the ground at various depths. The information is given in the form of curves showing the values for a complete year. Taking the abnormally hot years of 1911 and 1921, the ground temperature in Britain from November to April is below 10° C., and it only exceeded 15° C. during the months of June, July and August. The value of 15° C. adopted by the Association for the normal maximum ground temperature for Great Britain, therefore, is well above the actual mean value and is only exceeded during the period when the cables are likely to be lightly loaded.

The thermal resistance S of the cable, which is expressed in electrical measure per unit length of cable, depends on two factors:—

(*a*) The thermal resistivity of the dielectric.
(*b*) The lines of heat-flow from the conductor to the surface of the cable.

Regarding the dielectric, initial values given in the Preliminary Report (*Journal I.E.E.*, 1921, vol. 59, p. 181) showed variations of the order of from 400 to 1 200 in the value of the thermal constant K for cables made with apparently similar material. Further tests have therefore been made with modern cables, and as a result of these and of an investigation of the method of calculation, the values given on page 535 are recommended.

Since it is necessary to determine the thermal resistance of any size or type of cable from a knowledge of the thermal resistivity of the material, the lines of heat-flow through the dielectric and the extent to which they affect the value of thermal resistance are of primary importance. In the cases of single-core and concentric cables the problem is simple, but for multi-core cables the lines of heat-flow are complicated, and comparison of three existing formulæ due to Russell and to Mie made it clear that none of them was completely satisfactory.

Experimental determinations were therefore made, and it was found that considerable corrections were required. Russell's formula on account of its greater simplicity has been mainly used with the corrections evolved as a result of experiment. A curve of the errors for different sizes of cables is shown in Fig. 36. The errors range from 10 per cent for a cable as used for 20 000 volts to over 30 per cent for a 660-volt cable.

The thermal resistivity of the armouring and protective coverings taken as a whole has been determined for a number of cables and the value taken is based on these experimental determinations.

The thermal resistance G of the soil (page 535).— Here again two factors are involved.

(*a*) The thermal resistivity of the soil.
(*b*) The lines of heat-flow from the cable.

The thermal resistivity of the soil depends largely upon the amount of moisture present, and partly upon the type of soil. A full series of tests was made with both sandy loam and heavy clay, in order to determine the effect of varying moisture contents. Curves giving the values obtained are shown in Fig. 5. Sandy loam with a moisture content of 5 per cent has a thermal resistivity of 180, as compared with 90 for the same soil with 15 per cent of moisture. With heavy clay having about 17 per cent moisture—nearly the normal value for such soil—the value is 180.

As an example, a particular three-core 0·1 sq. in. 6 600-volt cable laid direct in the ground at a depth of 3 ft. would have a current rating of 228 amperes for a thermal resistivity of 90, and 192 amperes for a thermal resistivity of 180; the effect, however, varies with different sizes and types of cables, as may be seen by reference to the tables (see pages 524–533).

A large amount of data has been collected from various parts of the country, and in one case from abroad, giving the actual amount of moisture present in the soil at different periods of the year and under various climatic conditions. As a result it appeared that a fair average would be 10 per cent for sandy loam and 20 per cent for clay soil; but in view of the large differences possible, and especially in view of the opinion expressed that in some cases the soil around a continuously loaded cable becomes quite dry, it was decided to draw up load tables for four values of thermal resistivity corresponding to moisture contents ranging from 0 to 15 per cent for sandy loam, and 1 to about 20 per cent for heavy clay.

The appearance of soil is not a safe guide to its moisture content, as soil that is apparently quite dry is likely to contain 5 per cent of moisture.

The exact nature of the process of heat transmission through the soil has been the subject of much discussion, and various assumptions have been made regarding it. Kennelly in America and Teichmüller in Germany adopted a formula based on the assumption that the surface of the ground above the cable was an isothermal, which implies that all the heat was ultimately transmitted to the surface of the ground, which being in contact with free air remains at uniform temperature. An alternative was the assumption of Apt that the cable was surrounded by a series of concentric isothermals, which implies that the heat-flow proceeds uniformly in all directions. The assumptions of Kennelly and Teichmüller, although widely accepted, are not strictly accurate and the subject required data based on actual experiment. Special tests, in which all the usual variables were excluded, were therefore made to determine the shape of the isothermals of heat-flow under ideal conditions, and it was found that neither of the above assumptions was correct (see page 543). Further, a large number of tests have been made on cables of different sizes laid direct in the ground, and from these results, corrected to a common basis, in conjunction with the information obtained above on heat-flow the Kennelly formula was modified so that it more nearly fits the facts, and it is on this new basis that the current tables now submitted have been calculated.

Depth of laying (page 538).—The effect on the heating of a cable due to variation in the depth of laying can be calculated by an adaptation of the formula mentioned above. Experiments were made with three lengths of cable laid at different depths, and the results obtained are in fair agreement with those calculated. In the

specific case of a cable laid at various depths, the proportional values of the currents required to produce a given temperature-rise where all conditions were equal were 100, 97 and 92, at depths of 1 ft. 6 in., 2 ft. 6 in. and 4 ft. 6 in. respectively. This, however, must not be taken as a safe general rule, since it is likely that for a considerable part of the year the moisture content at a depth of 1 ft. 6 in. would be less than at 4 ft. 6 in., and that the ground temperature would be higher.

Other factors affecting the rating.

(*a*) Grouped cables laid direct in the ground (page 547).—The extent to which the rating of a cable is affected by the proximity of other cables has been investigated both theoretically and experimentally, and a method has been developed for the predetermination of the mutual effect of two or more cables. Practice as to conditions of laying varies enormously and no general rule can be given. The method must, therefore, be applied in each particular case. As an example, however, for two cables laid in the same horizontal plane in a trench the maximum permissible current would have to be reduced in the ratios shown in the following table (see Table 37):

Distance between Axes of Cables in Inches	Ratio of Maximum Permissible Currents for Two Cables
4	0·76
8	0·82
12	0·86

At a distance apart of from 4 ft. to 6 ft. the difference becomes almost inappreciable.

Where two cables are laid in the same trench and in the same vertical plane with 5 in. between the axes the ratios would be approximately as follows:—

With the uppermost cable 1 ft. 6 in. below the surface.

For a small cable .. .. 0·86
For a large cable .. .. 0·78

With the uppermost cable 3 ft. below the surface.

For a small cable .. .. 0·83
For a large cable .. .. 0·75

(*b*) Cables drawn into ducts (page 552).—The existing information available for cables drawn into ducts is meagre and not capable of general application. Moreover, in view of the lagging effect around the cable due to the air which may or may not be in motion, it appeared to be improbable that a general simple rule could be devised. Experiments were therefore made to determine the difference in the rating of cables of various sizes under the following conditions:

(i) When in air free from draughts.
(ii) When drawn into a duct.

The first depends entirely on the constants of the cable, so that comparison of the two sets of values should indicate the effect of the duct. The tests made showed that with all sizes of cable from 0·1 sq. in. concentric (external diameter = 1·1 in.) to 0·5 sq. in. concentric (external diameter = 2·1 in.) and 0·15 sq. in. three-core armoured (external diameter = 2·9 in.) the factor connecting the values of current for an equivalent rise of temperature in air varied from 0·98 to 0·935, the lower value being due probably to the armouring, which gave a somewhat different value in air. This made it clear that the greater part of the resistance to the flow of heat from the cable was in the thin layer of air immediately around the latter and that the relative size of cable and duct made little difference to the final result. It was decided, therefore, that current-loading tables for one plain lead-sheathed cable in a duct should be drawn up on the basis that the current required to produce the same temperature-rise in a cable in a duct is 0·95 of that for the same cable in air free from draughts.

(*c*) Grouped cables drawn into ducts (page 552).—Some tests have been made with the six-way duct shown in Fig. 20 in order to determine the effect of grouping, but these are not sufficient to allow of general application. Further experimental work is required on this subject.

Current-rating of cables in air (page 551).—All the cables used in the investigations have been tested in air free from draughts. Tests under this condition provide a satisfactory basis from which the behaviour under other conditions can be deduced in the light of the information now available as to the effect of laying direct in the ground or drawing into ducts. A formula has been developed which fits the experimental series very well, and the current-loading tables for cables drawn into ducts have been based on this. The values for the air conditions depend on the emissivity constant of the surface of the cable, among other factors. This constant varies with the nature of the surface, but there is not a great and consistent difference between the black surface of an armoured cable and a plain lead sheath. In cases when the lead sheath is new and bright the value is distinctly lower, but in general the values for both are of the same order, and it seems probable that when the surface of the lead has become dull the emissivity constant is substantially the same as for a black surface.

Current-rating of cables for cyclical intermittent loading (page 554).—It was suggested in the discussion on the Preliminary Report that use might be made of the thermal time-constant of a cable for the calculation of the short-time rating, but it was found that the method was not applicable, since a cable buried in the ground behaves essentially differently from one in air. In order to meet the case experiments were made with cables loaded in accordance with information given by electric supply authorities. In general the increase of current loading for intermittent load conditions is not large, varying from 3 per cent to 10 per cent, which amount was thought to be insufficient to justify a recommendation for increased rating for intermittent loading.

Current-rating of cables for emergency loading (page 560).—Two of the types of short-time cyclic loading referred to above were also designed to give information

on which to base a rating for one or two hours only, for use in emergency.

These figures show considerable increases over the maximum continuous permissible currents without exceeding the specified maximum temperature, and are more nearly independent of the method of laying. On the score of damage to the dielectric this temperature might be exceeded on emergency, but the same limit is retained to obviate damage due to abnormal expansion, especially differential expansion between conductor and lead.

As an example, a 0·15 sq. in., three-core, lead-covered and armoured cable as used for 20 000 volts laid direct in the ground, if running continuously at half its rated current, will thereafter carry for one hour 20 per cent or for two hours 13 per cent over and above the maximum continuous rating. In general, larger cables will carry a greater, and smaller cables a less, increment than the above.

Comparison between the heating of three-core cable with three-phase current and direct current (page 546).—Experiments were made to determine whether there was any appreciable increase of heating of a three-core armoured cable when loaded with three-phase alternating current as compared with that observed with an equal direct current. Tests were made with a 0·15 sq. in., three-core cable, lead-covered and wire armoured, at frequencies of 25 cycles and 50 cycles respectively. No measurable difference between these results and those obtained with direct current was found, and it seems clear that for a cable of this size the skin effect and eddy currents in the sheath do not produce any appreciable additional heating effect.

Work outstanding.—A statement is given of the work necessary to complete the investigation, dealing more particularly with cables for pressures above 11 000 volts.

List of Symbols.

The symbols generally adopted throughout the report are given below, all dimensions being in centimetres. They include all except a few which have been used incidentally and of which the meanings are explained in the body of the report as they occur.

a = distance of the axis of the conductor from the cable axis in a multi-core cable.
b = maximum distance between conductor and cable axis in three-core cables with segmental conductors.
c = minimum distance between conductor and cable axis in three-core cables with segmental conductors.
D = thickness of dielectric between conductors and between any conductor and lead sheath of three-core cables, centre point not earthed.
E = thickness of dielectric between any conductor and lead sheath of three-core cables, centre point earthed.
G = thermal resistance per cm length of cable between outer covering or sheath of the cable and surface of the ground in electrical measure.
g = thermal resistivity of the soil surrounding the cable expressed in the same units as K.
H = heat in watts developed in a cm length of each conductor.
h = emissivity constant, i.e. watts per degree C for 1 sq. cm.
I = current in each conductor.
K = thermal resistivity of dielectric in electrical measure, i.e. as a difference in degrees C. between opposite faces of a cm cube, to cause the transference of 1 watt of heat.
K_1 = thermal resistivity (mean) of protective coverings of cable.
L = depth of cable axis below the surface of the ground.
n = number of separate conductors.
R = resistance per cm length of each conductor at 15·6° C.
R_1 = resistance per cm length of each conductor at the temperature of operation.
r = radius of the conductor of a multicore cable.
r_1 = radius of the conductor in a single-core cable or of the inner conductor in a concentric cable.
r_2 = inner radius of the outer conductor of a concentric cable.
r_3 = outer radius of the outer conductor of a concentric cable.
r_4 = inner radius of the lead sheath.
r_5 = outer radius of the lead sheath.
r_6 = external radius of the outer covering of finished cable.
S = thermal resistance per cm length of cable between conductor and outer covering or sheath in electrical measure.
t or t_1 = temperature-rise of the conductor in degrees C.
t_2 = temperature-rise of the sheath in degrees C.
t_3 = temperature-rise of the outer conductor of a concentric cable in degrees C.

Tables of Maximum Permissible Currents (Continuous Loading) for Impregnated Paper-insulated Cables, together with Notes giving the Basis and Method of Calculation.

The current-loading Tables, 3 to 27 inclusive, refer to the following types of cable and methods of laying :—

(i) Armoured cables laid direct in the ground.
(ii) Armoured and unarmoured cables in air.
(iii) Unarmoured cables drawn into ducts.

The arrangement of the current-loading tables corresponds to that adopted in B.S.S. No. 7—1922, and the numbers of the Tables in that Specification have been added for convenience. Cross-sections of three-core cables are shown in Figs. 1 and 2.

Explanatory Notes.

General.—The fundamental relation connecting the quantities involved in the calculation of the current

that will produce a given temperature-rise in a buried cable is as follows:—

$$H = t_1/(S + G) \quad \ldots \quad (1)$$

H, the quantity of heat developed per unit length of the conductor (or conductors), is given by the equation

$$H = I^2nR(1 + at_1) \quad \ldots \quad (2)$$

or

$$I_t = \sqrt{\left[\frac{t}{nR(1 + at)(G + S)}\right]} \quad \ldots \quad (3)$$

where I_t = current in amperes in each conductor to produce a temperature-rise of t degrees C.

a = temperature coefficient of the conductor, equals 0·0040 at 15° C.

t = temperature-rise in degrees C. above 15·6° C.

For other symbols see List of Symbols (page 521).

Resistance of conductor.—In the calculation of the following current-loading tables for the specified cable sizes the values of R have in all cases been derived from B.S.S. No. 7—1922, Table 2, Col. 6, by multiplica-

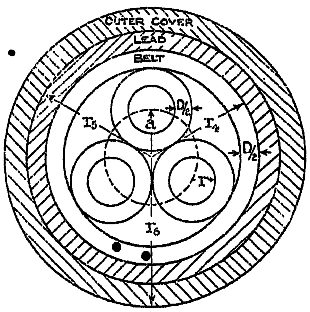

FIG. 1.—Cross-section of three-core cable, centre point not earthed.

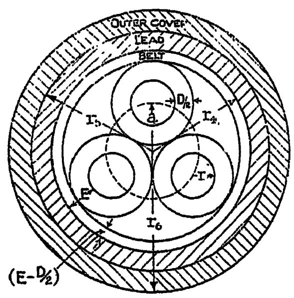

FIG. 2.—Cross-section of three-core cable, centre point earthed.

tion of the values there given, which are the standard resistances in ohms per 1 000 yards at 15·6° C., by the factor $10{\cdot}94 \times 10^{-6}$. The values so obtained are ohms per cm at 15·6° C.

The maximum temperature-rise for armoured cables laid direct in the ground being taken as 50 degrees C. with a ground temperature of 15° C. the temperature of the conductor is limited to 65° C. as a maximum, and the resistance per cm length under these conditions is obtained by multiplying the standard resistance R by

$$(1 + 0{\cdot}0040 \times 49{\cdot}4)\ *$$

The first term of the formula for I_t when t = 50 degrees C. is therefore

$$\frac{1}{\sqrt{[R(1 + 0{\cdot}0040 \times 49{\cdot}4)]}} = \frac{0{\cdot}9129}{\sqrt{R}} \quad \ldots \quad (4)$$

For cables in air and drawn into ducts the temperature-rise allowed is 35 deg. C., with an air temperature of 15° C., the maximum permissible temperature therefore being 50° C.

Evaluation of G and depth of laying.—The term G, on the Kennelly assumption, is defined by the following equation:—

$$G = \frac{g}{2\pi} \log_e \frac{2L}{r_6} \quad \ldots \quad (5)$$

The depth L was taken as 18 in. or 45·7 cm for cables for pressures from 660 up to and including 2 200 volts, and as 3 ft. or 91·4 cm for cables for pressures above 2 200 up to and including 11 000 volts.

The tables have been prepared for four values of thermal resistivity of the soil, viz. 340, 180, 120 and 90. It was found, however, that the best correspondence between theoretical calculations and experimental results was obtained if g were taken as having only two-thirds of the value obtained by direct experimental determination. The four values of the thermal resistance G, corresponding to the four values of the resistivity g mentioned above, are then given by the formulæ in Table 1.

TABLE 1.

Thermal Resistance (G) of the Soil per cm Length of Cable, between the Outer Covering of the Cable and the Surface of the Ground.

Limits of Working Pressure of Cable	Thermal Resistance of Soil	
	$g = 340$	$g = 180$
From 660 up to and including 2 200 volts	$36{\cdot}1 \log_e \frac{91{\cdot}4}{r_6}$	$19{\cdot}1 \log_e \frac{91{\cdot}4}{r_6}$
Above 2 200 up to and including 11 000 volts	$36{\cdot}1 \log_e \frac{182{\cdot}8}{r_6}$	$19{\cdot}1 \log_e \frac{182{\cdot}8}{r_6}$
	$g = 120$	$g = 90$
From 660 up to and including 2 200 volts	$12{\cdot}7 \log_e \frac{91{\cdot}4}{r_6}$	$9{\cdot}55 \log_e \frac{91{\cdot}4}{r_6}$
Above 2 200 up to and including 11 000 volts	$12{\cdot}7 \log_e \frac{182{\cdot}8}{r_6}$	$9{\cdot}55 \log_e \frac{182{\cdot}8}{r_6}$

As an example of the effect of depth of laying on the current rating, the two values of G for thermal resistivity 120 may be considered. Assuming r_6 as 2 cm for the lower pressure cables, i.e. for

L = 1 ft. 6 in., $G = 48{\cdot}5$;

for the higher-pressure cables, i.e. for

L = 3 ft. 0 in., $G = 57{\cdot}3$.

Thus, if the depth be doubled the term G is increased by about 18 per cent.

To obtain an indication of the effect of depth on the current-carrying capacity it may be assumed that S will be a quantity of approximately the same order as G. The current will then be inversely proportional to the square root of the sum of these two quantities, whence it follows that the effect in this particular instance of doubling the depth at which the cable is laid will be to diminish the current-carrying capacity

* The values for the standard resistance R given in B.S.S. No. 7—1922, are at 15·6° C. A temperature-rise of 50 degrees C. above 15° C. therefore corresponds to 49·4 degrees C. above 15·6° C.

by some 4 or 5 per cent. This is, of course, on the assumption that the moisture content throughout the soil is the same and that the soil is thermally homogeneous.

Dimensions of conductors.—The overall diameters of the conductors for the sizes of cable dealt with in the current-loading tables are given in Table 2.

In the case of stranded conductors, the overall diameter of the conductor was derived from B.S.S. No. 7—1922, Table 2, Col. 3, and was taken as being equal to the sum of the diameters of the maximum number of component wires lying on any diameter of the strand.

Thermal resistance of cable.—The thermal resistance S may be conveniently regarded in the case of an armoured cable as made up of two portions S_1 and S_2 such that $S_1 + S_2 = S$, and where :—

S_1 = thermal resistance between the conductor (or conductors) and the sheath ;

S_2 = thermal resistance between the sheath and the outer surface of the cable (protective covering).

The derivation of S_1 from the thermal constants assumed and the dimensions given in Table 2 above and in B.S.S. No. 7—1922, is as follows :—

S_1 = resistance between conductor(s) and sheath

(*a*) Single-core cables :

$$S_1 = \frac{K}{2\pi}\log_e\left(\frac{r_4}{r_1}\right) = \frac{K}{2\pi}\log_e\left[\frac{r_1 + D}{r_1}\right] \qquad (6)$$

(*b*) Concentric cables :

$$S_1 = \frac{K}{2\pi}\left[\tfrac{1}{2}\log_e\left(\frac{r_2}{r_1}\right) + \log_e\left(\frac{r_2}{r_3}\right)\right] \quad . \quad . \quad (7)$$

The value of r_1 is obtained from Table 2 which gives the diameter of the completed strand—

$$r_2 = r_1 + D \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where D is the thickness of dielectric as specified in B.S.S. No. 7—1922.

To obtain r_3, the thickness U of the outer conductor is added to r_2.

In order to obtain a simple expression for U it was taken that, to a first approximation—

$$U = s/2\pi(r_1 + D) \quad . \quad . \quad . \quad . \quad (9)$$

where s is the nominal area of conductor cross-section.

Therefore $r_3 = r_1 + D + s/[2\pi(r_1 + D)]$ . . (10)

and $r_4 = r_1 + 2D + s/[2\pi(r_1 + D)]$ . . (11)

so that

$$S_1 = \frac{K}{2\pi}\left\{\tfrac{1}{2}\log_e\left(\frac{r_2}{r_1}\right) + \log_e\left[\frac{r_1 + 2D + s/2(r_1 + D)}{r_1 + D + s/2(r_1 + D)}\right]\right\} \quad . \quad (12)$$

(*c*) Three-core cables (circular conductors; centre point not earthed) :

TABLE 2.

Sizes of Conductors dealt with in the Current-loading Tables.

Sectional Area of Conductor		Number and Diameter (in.) of Wires comprising Conductor	Maximum Number of Component Wires on a Diameter	Overall Diameter of Complete Strand	
Nominal sq. in.	Calculated sq. in.			in.	cm
0·007	0·007005	7/·036	3	0·108	0·274
0·01	0·01046	7/·044	3	0·132	0·335
0·0145	0·01462	7/·052	3	0·156	0·396
0·0225	0·02214	7/·064	3	0·192	0·487
0·03	0·02840	19/·044	5	0·220	0·558
0·04	0·03960	19/·052	5	0·260	0·660
0·06	0·05999	19/·064	5	0·320	0·812
0·075	0·07592	19/·072	5	0·360	0·914
0·1	0·1009	19/·083	5	0·415	1·05
0·12	0·1168	37/·064	7	0·448	1·14
0·15	0·1478	37/·072	7	0·504	1·28
0·2	0·1964	37/·083	7	0·581	1·47
0·25	0·2465	37/·093	7	0·651	1·65
0·3	0·3024	37/·103	7	0·721	1·83
0·4	0·4064	61/·093	9	0·837	2·12
0·5	0·4985	61/·103	9	0·927	2·35
0·6	0·6062	91/·093	11	1·028	2·60
0·75	0·7435	91/·103	11	1·133	2·87
1·0	1·0376	127/·103	13	1·339	3·38

In order to derive the dimensions needed for the calculation of the thermal resistance of a three-core cable from the thickness of the dielectric and the diameter of the conductor the following geometrical relations are required (see Fig. 1).

$$a = 1\cdot 154(r + \tfrac{1}{2}D) \quad . \quad . \quad . \quad . \quad (13)$$

$$r_4 = a + r + D = 1\cdot 58D + 2\cdot 15r \quad . \quad (14)$$

By Equation (33) (Russell's formula for three-core cables)

$$S_1 = \frac{K}{6\pi}\log_e\left[(r_4^6 - a^6)/3r_4^3a^2r\right] \quad . \quad . \quad (15)$$

or substituting for a and r_4 and neglecting a^6 in comparison with r_4^6

$$S_1 = K \times 0\cdot 053 \log_e\left[\frac{3\cdot 93(D + 1\cdot 37r)^3}{(D + 2r)^2r}\right] \quad (16)$$

(*d*) Three-core cables (circular conductors; centre point earthed):

Here the thickness of the belt insulation E is reduced (see Fig. 2) and the formulæ are modified as follows:—

$$r_4 = a + r + E = 0\cdot 58D + 2\cdot 15r + E \quad . \quad (17)$$

and from Russell's formula, Equation (33) neglecting a^6 in comparison with r_4^6

$$S_1 = \frac{K}{6\pi}\log_e\left[\frac{0\cdot 58D + 2\cdot 15r + E}{r(2r + D)^2}\right] \quad (18)$$

In calculating S_1, the thermal resistivity of the dielectric was taken in general as 750 for cables for pressures up to 2 200 volts, and as 550 for cables for pressures above 2 200 volts up to and including 11 000 volts.

Higher values were taken for cables with conductors having sectional areas less than 0·06 sq. in., to allow for the difficulty in manufacturing small cables.

The value of S_2 the thermal resistance of the protective coverings was determined as follows:—

The outer radius of the lead sheath r_5 was found by adding the thickness of the lead as specified in Tables 5 to 10 of B.S.S. No. 7—1922, to the internal diameter of the lead sheath.

For single-core cables

$$r_5 = l + D + r_1 \quad . \quad . \quad . \quad . \quad (19)$$

For concentric cables

$$r_5 = l + r_4 = l + r_1 + 2D + s/2\pi(r_1 + D) \quad . \quad (20)$$

For three-core cables

$$r_5 = l + r_4 = l + 1\cdot 58D + 2\cdot 15r \quad . \quad . \quad (21)$$

The thickness of the armouring and protective coverings and r_6 the radius of the completed cable have been derived from the dimensions specified in Tables 18 and 21 of B.S.S. No 7—1922, for various sizes of cable. In order to obtain a mean value of cable covering, it has been assumed that the armouring consists of a single layer of galvanized wire. The value of the thermal resistivity determined for the protective covering, taken as a whole, i.e. wire armouring, bedding, braiding and serving, was $K_1 = 300$. This value refers to new cables only. The effect of the protective covering is small and for the purpose of the calculations it was convenient and sufficiently accurate to regard it as being thermally homogeneous, with a mean value of thermal resistivity, $K_1 = 300$.

For S_2, the thermal resistance of the covering, we have

$$S_2 = \frac{K_1}{2\pi}\log_e\left(\frac{r_6}{r_5}\right) \quad . \quad . \quad . \quad . \quad (22)$$

Three-core cables with segmental conductors.—The increased current-ratings for three-core cables with segmental conductors are suggested tentatively, as they are based almost entirely on theoretical considerations with the adoption of certain assumptions for dimensions and shapes. Standard dimensions are required before more definite values can be given for this type of cable.

"Skin effect" in large cables.—The current-loading tables make no allowance for the additional heating due to "skin effect" when cables having conductors larger than 0·25 sq. in. are carrying alternating current at a frequency of 50 cycles per second or higher. Such cables are usually constructed with an inner hemp core, and are designed so as to minimize "skin effect."

Earthed system.—In accordance with Clause 35 of B.S.S. No. 7—1922 an earthed system is one which is permanently connected to earth in such a manner that the total earth resistance does not exceed 2 ohms, or one in which a device is installed that automatically and instantly cuts out any part of the system that becomes accidentally earthed.

TABLE 3.

660-*volt, Armoured, Single-core Cable, laid Direct in the Ground* (Table 5, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)			
		Thermal Resistivity of Soil (g)			
Nominal	Calculated	$g = 340$	$g = 180$	$g = 120$	$g = 90$
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·007	0·007005	54	60	63	65
0·01	0·01046	70	79	83	86
0·0145	0·01462	86	100	106	110
0·0225	0·02214	112	131	141	147
0·03	0·02840	131	155	167	175
0·04	0·03960	160	190	207	218
0·06	0·05999	205	248	273	287
0·075	0·07592	234	285	314	332
0·1	0·1009	275	337	373	395
0·12	0·1168	299	367	407	435
0·15	0·1478	341	415	459	486
0·2	0·1964	401	492	547	580
0·25	0·2465	455	558	621	661
0·3	0·3024	510	627	699	743
0·4	0·4064	602	745	831	886
0·5	0·4985	677	835	935	998
0·6	0·6062	757	942	1 056	1 131
0·75	0·7435	848	1 055	1 186	1 269
1·0	1·0376	1 027	1 282	1 448	1 556

TABLE 4.

660-*volt, Armoured, Concentric Cable, laid Direct in the Ground; Earthed or Not Earthed* (Table 5, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading) — Thermal Resistivity of Soil (g)			
Nominal	Calculated	$g = 340$	$g = 180$	$g = 120$	$g = 90$
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·007	0·007005	39	44	46	47
0·01	0·01046	50	57	60	62
0·0145	0·01462	62	72	76	79
0·0225	0·02214	81	94	101	105
0·03	0·02840	95	111	120	126
0·04	0·03960	115	136	148	155
0·06	0·05999	147	176	191	201
0·075	0·07592	168	202	221	233
0·1	0·1009	198	239	262	277
0·12	0·1168	215	260	286	302
0·15	0·1478	246	299	329	346
0·2	0·1964	289	353	391	413
0·25	0·2465	329	400	443	470
0·3	0·3024	369	453	503	535
0·4	0·4064	435	534	592	630
0·5	0·4985	486	605	675	718
0·6	0·6062	551	687	762	813
0·75	0·7435	616	765	855	910
1·0	1·0376	747	936	1 050	1 126

TABLE 5.

660-*volt, Armoured, Three-core* Cable, laid Direct in the Ground; Centre Point Earthed or Not Earthed* (Table 5, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading) — Thermal Resistivity of Soil (g)			
Nominal	Calculated	$g = 340$	$g = 180$	$g = 120$	$g = 90$
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·007	0·007005	35	40	43	44
0·01	0·01046	45	52	56	58
0·0145	0·01462	55	66	70	73
0·0225	0·02214	71	84	91	95
0·03	0·02840	82	98	106	111
0·04	0·03960	100	120	131	138
0·06	0·05999	127	154	169	179
0·075	0·07592	145	176	194	205
0·1	0·1009	170	208	229	244
0·12	0·1168	185	226	251	267
0·15	0·1478	211	260	288	306
0·2	0·1964	248	305	339	361
0·25	0·2465	283	349	389	413
0·3	0·3024	318	391	436	465
0·4	0·4064	373	460	512	547
0·5	0·4985	420	520	582	621

* The current values given in this table refer to cables with circular conductors; the rating may be increased by [illegible] per cent for cables with segmental conductors. When two conductors only are carrying current (three-wire system, balanced load), the current values given in this table may be increased by 15 per cent.

TABLE 6.

2 200-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 6, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading) — Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Outer Conductor		Outer Conductor		Outer Conductor		Outer Conductor	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	79	81	90	93	95	99	98	102
0·03	0·02840	92	94	106	109	113	117	117	121
0·04	0·03960	112	114	130	134	139	145	145	150
0·06	0·05999	144	146	169	174	182	190	190	198
0·075	0·07592	165	167	194	200	210	218	219	229
0·1	0·1009	194	196	230	236	249	258	260	272
0·15	0·1478	242	245	287	294	313	324	328	342
0·2	0·1964	284	288	340	349	373	385	391	406
0·25	0·2465	324	328	391	399	430	442	454	468

Table 7.

2 200-*volt, Armoured, Three-core* * *Cable, laid Direct in the Ground* (Table 6, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Centre Point		Centre Point		Centre Point		Centre Point	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	70	71	81	83	88	90	91	93
0·03	0·02840	81	82	95	97	103	105	107	110
0·04	0·03960	98	99	116	118	127	129	132	135
0·06	0·05999	125	126	150	152	163	165	170	174
0·075	0·07592	143	144	172	174	188	191	198	202
0·1	0·1009	168	169	203	205	222	226	235	239
0·15	0·1478	209	210	251	254	279	283	293	299
0·2	0·1964	245	247	297	301	329	335	348	355
0·25	0·2465	279	281	340	345	376	384	399	408

* The current values given in this table refer to cables with circular conductors; the rating may be increased by 3 per cent for cables with segmental conductors.

Table 8.

3 300-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 7, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Outer Conductor		Outer Conductor		Outer Conductor		Outer Conductor	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	79	80	92	95	100	103	104	108
0·03	0·02840	92	93	108	111	117	121	123	127
0·04	0·03960	111	113	132	135	143	148	150	156
0·06	0·05999	141	143	170	174	187	192	196	204
0·075	0·07592	161	163	194	199	214	220	226	234
0·1	0·1009	189	191	229	234	253	260	268	276
0·15	0·1478	233	236	285	291	316	325	335	345
0·2	0·1964	273	276	336	342	374	383	398	409
0·25	0·2465	312	314	385	391	430	437	458	469

TABLE 9.

3 300-*volt, Armoured, Three-core* Cable, laid Direct in the Ground* (Table 7, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Currents (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Centre Point		Centre Point		Centre Point		Centre Point	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	69	70	82	83	90	92	95	97
0·03	0·02840	80	81	96	97	106	108	111	113
0·04	0·03960	96	97	117	118	129	131	137	139
0·06	0·05999	121	122	149	150	165	167	176	178
0·075	0·07592	138	139	170	171	189	191	210	204
0·1	0·1009	162	163	200	201	223	225	238	241
0·15	0·1478	200	201	249	250	277	279	297	300
0·2	0·1964	235	236	293	294	329	331	352	355
0·25	0·2465	266	267	333	334	374	376	402	405

* The current values given in this table refer to cables with circular conductors; the rating may be increased by 2 per cent for cables with segmental conductors.

TABLE 10.

5 500-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 8, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Outer Conductor		Outer Conductor		Outer Conductor		Outer Conductor	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	78	80	90	95	97	102	101	107
0·03	0·02840	91	93	106	110	114	120	119	126
0·04	0·03960	110	112	130	135	140	147	147	155
0·06	0·05999	140	143	167	173	182	190	191	201
0·075	0·07592	159	162	191	198	208	218	219	231
0·1	0·1009	186	190	225	233	247	258	260	274
0·15	0·1478	231	235	280	289	309	321	327	342
0·2	0·1964	271	276	330	341	364	380	385	402
0·25	0·2465	308	313	376	388	415	430	441	460

TABLE 11.

5 500-*volt, Armoured, Three-core* Cable, laid Direct in the Ground* (Table 8, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
Nominal	Calculated	Centre Point		Centre Point		Centre Point		Centre Point	
		Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	68	69	81	83	89	90	93	95
0·03	0·02840	79	80	95	97	103	105	109	111
0·04	0·03960	96	97	115	117	126	128	133	135
0·06	0·05999	121	122	147	149	163	165	173	175
0·075	0·07592	138	139	168	170	187	189	198	201
0·1	0·1009	161	162	198	200	220	223	234	237
0·15	0·1478	199	201	246	248	274	277	292	295
0·2	0·1964	233	235	289	292	323	326	344	348
0·25	0·2465	264	266	328	331	369	372	393	399

* The current values given in this table refer to cables with either circular or segmental conductors.

TABLE 12.

6 600-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 9, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
Nominal	Calculated	Outer Conductor		Outer Conductor		Outer Conductor		Outer Conductor	
		Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	78	80	90	94	96	101	100	106
0·03	0·02840	91	93	105	110	114	119	118	125
0·04	0·03960	109	112	129	134	139	145	145	153
0·06	0·05999	139	142	166	172	180	188	188	199
0·075	0·07592	158	162	190	197	207	217	218	229
0·1	0·1009	186	190	223	231	244	255	257	272
0·15	0·1478	230	235	276	286	304	318	321	338
0·2	0·1964	270	275	327	339	360	375	382	400
0·25	0·2465	307	312	374	387	413	428	438	458

TABLE 13.

6 600-*volt, Armoured, Three-core Cable,* laid Direct in the Ground* (Table 9, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Centre Point		Centre Point		Centre Point		Centre Point	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	68	68	81	82	88	89	92	94
0·03	0·02840	79	80	94	96	103	105	108	111
0·04	0·03960	95	96	114	116	125	128	133	136
0·06	0·05999	121	121	147	149	162	165	172	175
0·075	0·07592	137	138	168	169	185	188	196	200
0·1	0·1009	161	162	197	199	219	221	232	235
0·15	0·1478	199	200	245	247	273	276	290	295
0·2	0·1964	233	234	287	290	321	325	341	346
0·25	0·2465	265	265	328	330	366	371	391	397

The current values given in this table refer to cables with either circular or segmental conductors.

TABLE 14.

11 000-*volt, Armoured, Concentric Cable, laid Direct in the Ground* (Table 10, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Outer Conductor		Outer Conductor		Outer Conductor		Outer Conductor	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	76	79	87	92	93	100	96	103
0·03	0·02840	88	92	102	108	108	117	112	122
0·04	0·03960	106	111	123	132	131	143	136	149
0·06	0·05999	138	141	161	169	174	185	181	194
0·075	0·07592	156	160	183	192	198	211	206	221
0·1	0·1009	183	188	217	228	235	250	245	265
0·15	0·1478	227	233	269	283	293	312	307	330
0·2	0·1964	266	273	317	333	346	369	363	391
0·25	0·2465	302	310	362	380	395	422	416	447

TABLE 15.

11 000-*volt, Armoured Cable, Three-core,* laid Direct in the Ground* (Table 10, B.S.S. No. 7—1922).

Area of Conductor		Maximum Permissible Current (Continuous Loading)							
		Thermal Resistivity of Soil (g)							
		$g = 340$		$g = 180$		$g = 120$		$g = 90$	
		Centre Point		Centre Point		Centre Point		Centre Point	
Nominal	Calculated	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed	Not Earthed	Earthed
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.	amps.	amps.
0·0225	0·02214	67	70	79	81	85	89	89	93
0·03	0·02840	78	80	92	95	100	103	104	109
0·04	0·03960	95	96	112	116	122	127	128	134
0·06	0·05999	120	121	144	147	158	162	166	171
0·075	0·07592	137	138	165	168	181	186	191	196
0·1	0·1009	160	162	193	198	213	219	225	232
0·15	0·1478	197	199	240	245	265	271	279	287
0·2	0·1964	232	234	283	287	313	319	331	339
0·25	0·2465	263	265	321	326	357	363	379	388

* The current values given in this table refer to cables with either circular or segmental conductors.

TABLE 16.

660-*volt Cables in Air* (Table 5, B.S.S. No. 7—1922).

Area of Conductor.		Armoured			Unarmoured		
Nominal.	Calculated.	Single	Concentric	3-Core *	Single	Concentric	3-Core *
sq. in.	sq. in.	amps.	amps.	amps.	amps.	amps.	amps.
0·007	0·007005	46	35	31	39	31	28
0·01	0·01046	60	45	41	50	40	37
0·0145	0·01462	75	56	51	63	50	46
0·0225	0·02214	98	74	68	82	66	61
0·03	0·02840	115	87	80	97	78	72
0·04	0·03960	141	109	99	120	98	90
0·06	0·05999	185	144	129	161	129	119
0·075	0·07592	214	166	149	189	150	139
0·1	0·1009	255	197	180	224	180	169
0·12	0·1168	280	216	197	249	198	186
0·15	0·1478	332	251	228	290	231	218
0·2	0·1964	397	301	274	351	281	265
0·25	0·2465	457	348	317	413	328	309
0·3	0·3024	522	397	361	475	377	355
0·4	0·4064	628	478	435	583	461	433
0·5	0·4985	717	548	498	670	533	498
0·6	0·6062	817	614	—	772	612	—
0·75	0·7435	933	712	—	886	702	—
1·0	1·0376	1 158	888	—	1 120	888	—

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 4 per cent for cables with segmental conductors. When two conductors only are carrying current (three-wire system, balanced load), the current values given in this column may be increased by 15 per cent.

TABLE 17.

2 200-volt Cables in Air; Earthed or not Earthed (Table 6, B.S.S. No. 7—1922).

Area of Conductor		Armoured		Unarmoured	
Nominal	Calculated	Concentric	3-Core*	Concentric	3-Core*
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·0225	0·02214	74	68	69	63
0·03	0·02840	88	80	81	74
0·04	0·03960	107	98	100	91
0·06	0·05999	142	128	132	121
0·075	0·07592	164	149	152	141
0·1	0·1009	195	177	183	169
0·15	0·1478	247	225	233	217
0·2	0·1964	294	270	281	264
0·25	0·2465	342	312	327	305

* The current values given in these columns refer to cables with circular conductors; the rating may be increased by 3 per cent for cables with segmental conductors.

TABLE 18.

3 300-volt Cables in Air; Earthed or not Earthed (Table 7, B.S.S. No. 7—1922).

Area of Conductor		Armoured		Unarmoured	
Nominal	Calculated	Concentric	3-Core*	Concentric	3-Core*
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·0225	0·02214	80	72	74	66
0·03	0·02840	94	84	87	78
0·04	0·03960	115	104	107	97
0·06	0·05999	150	135	140	127
0·075	0·07592	173	156	161	147
0·1	0·1009	205	185	193	177
0·15	0·1478	259	235	245	228
0·2	0·1964	309	283	295	275
0·25	0·2465	359	326	344	321

* The current values given in these columns refer to cables with circular conductors; the rating may be increased by 2 per cent for cables with segmental conductors.

TABLE 19.

5 500-volt Cables in Air; Earthed or not Earthed (Table 8, B.S.S. No. 7—1922).

Area of Conductor		Armoured		Unarmoured	
Nominal	Calculated	Concentric	3-Core*	Concentric	3-Core*
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·0225	0·02214	79	72	75	68
0·03	0·02840	93	84	88	79
0·04	0·03960	115	104	109	98
0·06	0·05999	149	135	141	129
0·075	0·07592	172	155	164	149
0·1	0·1009	204	185	195	180
0·15	0·1478	257	235	248	230
0·2	0·1964	307	280	297	276
0·25	0·2465	353	323	343	320

* The current values given in these columns refer to cables with either circular or segmental conductors.

TABLE 20.

6 600-volt Cables in Air; Earthed or not Earthed (Table 9, B.S.S. No. 7—1922).

Area of Conductor		Armoured		Unarmoured	
Nominal	Calculated	Concentric	3-Core*	Concentric	3-Core*
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·0225	0·02214	79	72	75	68
0·03	0·02840	93	84	89	80
0·04	0·03960	115	104	109	98
0·06	0·05999	149	135	142	129
0·075	0·07592	172	156	164	150
0·1	0·1009	203	185	195	179
0·15	0·1478	257	235	249	229
0·2	0·1964	306	279	297	276
0·25	0·2465	353	322	344	320

* The current values given in these columns refer to cables with either circular or segmental conductors.

TABLE 21.

11 000-*volt Cables in Air; Earthed or not Earthed* (Table 10, B.S.S. No. 7—1922).

Area of Conductor		Armoured		Unarmoured	
Nominal	Calculated	Concentric	3-Core*	Concentric	3-Core*
sq. in.	sq. in.	amps.	amps.	amps.	amps.
0·0225	0·02214	78	72	77	70
0·03	0·02840	92	84	90	82
0·04	0·03960	112	104	109	101
0·06	0·05999	148	135	146	132
0·075	0·07592	169	155	166	153
0·1	0·1009	201	184	198	182
0·15	0·1478	254	232	250	231
0·2	0·1964	301	275	298	277
0·25	0·2465	346	319	344	320

* The current values given in these columns refer to cables with either circular or segmental conductors.

TABLE 22.

660-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 5, B.S.S. No. 7—1922).

Area of Conductor		Single	Concentric	3-Core*
Nominal	Calculated			
sq. in.	sq. in.	amps.	amps.	amps.
0·007	0·007005	37	30	27
0·010	0·01046	48	39	35
0·0145	0·01462	60	48	44
0·0225	0·02214	78	63	58
0·03	0·02840	92	74	68
0·04	0·03960	114	93	86
0·06	0·05999	153	122	113
0·075	0·07592	180	142	132
0·1	0·1009	213	171	161
0·12	0·1168	237	188	177
0·15	0·1478	275	219	207
0·2	0·1964	334	267	252
0·25	0·2465	393	311	294
0·3	0·3024	451	358	337
0·4	0·4064	554	437	412
0·5	0·4985	636	507	474
0·6	0·6062	733	581	—
0·75	0·7435	842	667	—
1·0	1·0376	1 065	843	—

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 4 per cent for cables with segmental conductors. When two conductors only are carrying current (three-wire system, balanced load), the current values given in this column may be increased by 15 per cent.

TABLE 23.

2 200-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 6, B.S.S. No. 7—1922).

Area of Conductor		Concentric	3-Core*
Nominal	Calculated		
sq. in.	sq. in.	amps.	amps.
0·0225	0·02214	65	60
0·03	0·02840	77	70
0·04	0·03960	95	86
0·06	0·05999	125	115
0·075	0·07592	144	134
0·1	0·1009	174	160
0·15	0·1478	221	206
0·2	0·1964	267	251
0·25	0·2465	311	290

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 3 per cent for cables with segmental conductors.

TABLE 24.

3 300-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 7, B.S.S. No. 7—1922).

Area of Conductor		Concentric	3-Core*
Nominal	Calculated		
sq. in.	sq. in.	amps.	amps.
0·0225	0·02214	70	63
0·03	0·02840	82	74
0·4	0·03960	102	92
0·06	0·05999	133	121
0·075	0·07592	153	140
0·1	0·1009	183	168
0·15	0·1478	233	217
0·2	0·1964	280	261
0·25	0·2465	327	305

* The current values given in this column refer to cables with circular conductors; the rating may be increased by 2 per cent for cables with segmental conductors.

TABLE 25.

5 500-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 8, B.S.S. No. 7—1922).

Area of Conductor		Concentric	3-Core*
Nominal	Calculated		
sq. in.	sq. in.	amps.	amps.
0·0225	0·02214	71	65
0·03	0·02840	83	75
0·04	0·03960	104	93
0·06	0·05999	134	123
0·075	0·07592	156	141
0·1	0·1009	185	171
0·15	0·1478	236	219
0·2	0·1964	282	262
0·25	0·2465	326	304

TABLE 26.

6 600-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 9, B.S.S. No. 7—1922).

Area of Conductor		Concentric	3-Core*
Nominal	Calculated		
sq. in.	sq. in.	amps.	amps.
0·0225	0·02214	71	65
0·03	0·02840	84	76
0·04	0·03960	104	93
0·06	0·05999	135	123
0·075	0·07592	156	142
0·1	0·1009	185	170
0·15	0·1478	237	218
0·2	0·1964	282	262
0·25	0·2465	327	304

TABLE 27.

11 000-*volt Unarmoured Cable in Duct; Earthed or not Earthed* (Table 10, B.S.S. No. 7—1922).

Area of Conductor		Concentric	3-Core*
Nominal	Calculated		
sq. in.	sq. in.	amps.	amps.
0·0225	0·02214	73	66
0·03	0·02840	85	78
0·04	0·03960	104	96
0·06	0·05999	139	125
0·075	0·07592	158	145
0·1	0·1009	188	173
0·15	0·1478	238	220
0·2	0·1964	283	263
0·25	0·2465	327	304

* The current values given in this column refer to cables with either circular or segmental conductors.

THEORETICAL AND EXPERIMENTAL WORK.

Since the issue of the Preliminary Report, the investigation has been directed to obtaining the information necessary to enable final current-loading tables for cables to be drawn up. The factors regarding which further information was required, and also points which were raised in the discussion that took place on the Preliminary Report, may be included in a brief restatement of the problem.

Apart from the dielectric losses, which are negligible for the cables dealt with in this report, the maximum permissible current-loading of cables depends on the following factors:—

(*a*) The power losses in the cable.
(*b*) The thermal constants of the dielectric and protective coverings.
(*c*) The thermal constants of the surrounding soil, which depend on such factors as the moisture content and the depth of laying.
(*d*) The temperature of the ground.
(*e*) The expansion of cables.
(*f*) The maximum temperature to which it is permissible to expose the dielectric and conductor.
(*g*) The mutual influence of neighbouring cables when two or more are laid together in the same trench.
(*h*) The effect on the current-rating when cables are drawn into ducts or laid " on the solid system."
(*j*) Any modification of the rating permissible when a cable is not loaded continuously at its maximum current (this is the more usual case in practice).

The factors given above are here considered in detail, and various other points relevant to the heating of buried cables are dealt with.

(1) POWER LOSSES IN THE CABLE.

Apart from losses occurring in the dielectric, which are negligible for the cables dealt with in this report, the power losses will depend on the current and the resistance of the conductor. Small variations may, and will be, found in individual lengths of cable, but the permissible limits of variation of conductor resistances are specified in B.S.S. No. 7—1922. As many as 29 cables were tested, details of which are given in Appendix I; and actual measurements showed that while several of the conductors were not very close to the specified dimensions, the resistivity of 230 samples of copper taken from the different cables varied only from 0·1513 to 0·1588 ohm per metre-gramme at 20° C., the higher value being probably the result of war-time and later difficulties with copper supplies.

The resistivity of the copper in cables supplied prior to 1914 rarely exceeded 0·153 ohm per metre-gramme, the usual value being 0·152 or even less.

The average temperature coefficient of 47 of the samples was 0·00390 at 20° C., or nearly 0·0040 at 15° C.

(2) THERMAL CONSTANTS OF IMPREGNATED PAPER DIELECTRIC.

The results obtained with the cables first laid suggested that the thermal resistivity of the dielectric might vary with different cables to a larger extent than had hitherto been supposed. Determinations* were therefore made with all cables then available, which included a length of six-core cable for split-conductor working (each conductor circular), and one of three-core concentric split-conductor cable, provided by the Glasgow Corporation. These were supplemented later by six lengths of three-core cable from different makers, with dielectric as frequently used for 20 000-volt working, supplied through the Cable Makers' Association.

The thermal resistivity of the cables was determined by measuring the temperature of the conductor and the lead sheath by change of resistance, the dimensions of the cable being known. It was assumed that the heat distribution throughout the conductor was uniform, and also that there was no appreciable temperature gradient in the lead. All the American and German authorities have neglected any gradient in the lead sheath, and this is justified by consideration of the thermal resistivity of the lead as compared with that of a paper and oil dielectric.

The thermal resistivity of lead is $2 \cdot 9$, as compared with (say) 500 for the dielectric; thus, with a temperature gradient of 20 degrees C. between the conductor and the outside of the lead sheath, the gradient in the sheath would be of the order of only $0 \cdot 1$ degree C.

The thermal resistivity was calculated by means of the following formulæ adapted from those given by Dr. A. Russell.*

For single-core cables the thermal resistivity

$$K = \frac{2\pi(t_1 - t_2)}{H \log_e (r_4/r_1)} \quad . \quad . \quad . \quad . \quad (23)$$

where H = total heat in watts developed in each cm length of conductor.

r_1 = radius of the conductor.

r_4 = inner radius of the lead sheath.

$t_1 - t_2$ = temperature difference between the conductor and the lead sheath.

For a concentric cable

$$K = \frac{2\pi(t_1 - t_2)}{H[\frac{1}{2}\log_e (r_2/r_1) + \log_e (r_4/r_3)]} \quad . \quad . \quad (24)$$

where H = total heat in watts developed in each cm length of each conductor.†

r_1 = radius of the inner conductor.

r_2 = inner radius of the outer conductor.

r_3 = outer radius of the outer conductor.

r_4 = inner radius of the lead sheath.

And for multi-core cables

$$K = \frac{4\pi(t_1 - t_2)}{H\frac{2}{n}\log_e\left\{\frac{r_4^{2n} - a^{2n}}{nr_4^n \times a^{n-1} \times r}\right\}} \quad . \quad . \quad (25)$$

where a = radius of circle on which the centres of the conductors lie.

H = total heat in watts developed in each cm length of each conductor.

n = number of separate conductors in the cable.

r = radius of each conductor.

The thermal resistivity K thus obtained is expressed in terms of the difference of temperature in degrees C. required to cause the flow of one joule of heat per second between opposite faces of a cm cube. One joule of heat per second expressed in electrical measure is one watt, and equals $0 \cdot 24$ gramme-calorie per second.

The formula for multi-core cables is subject to considerable error except where the size of the conductors is very small as compared with the total diameter of the sheath. Alternative formulæ by Mie * were examined by Mr. S. Butterworth, of the National Physical Laboratory, whose conclusions are given in Appendix II. The examination indicates that Mie's formulæ are subject to considerable error and, moreover, values calculated by Russell's formula are very different from those obtained by Mie's formula. It was therefore considered advisable to make some experimental determinations to check the formulæ and to evaluate the amount of the correction required.

Various methods were considered and it was finally decided to construct an electrostatic model of the cable; this consisted of a large metal tube corresponding to the lead sheath of the cable, with three smaller tubes corresponding to the conductors placed inside. Various sets of inner tubes were available, corresponding to different sizes of conductors, and the apparatus permitted of the arrangement and spacing of the inner tubes being varied. They were carefully insulated from the outer tube and the apparatus then formed a condenser the capacity of which could be accurately determined by appropriate methods.

The thermal resistance can then be deduced by means of the analogy between electrostatic capacity and resistance.

Mr. D. W. Dye of the National Physical Laboratory gave valuable advice and assistance in connection with this electrostatic method.

The detailed account of this portion of the investigation is given in Appendix III.

As a result of this investigation the error curve shown in Fig. 36 was obtained for the Russell formula, which on account of its greater simplicity was preferred for general use (see Appendix IV).

Table 28 gives the values of thermal resistivity obtained for all the cables tested. In the case of the three-core cables two sets of values are given: (1) those evaluated by means of the Russell formula without correction as given in the Preliminary Report; and (2) the values corrected in accordance with the error curve.

The table includes also some values for bitumen filling and non-impregnated paper.

It will be seen from Table 28 that the higher values occur more generally with the older 660-volt cables, and the lower values with the modern cables as fre-

* "Theory of Electric Cables," p. 217 *et seq.*

† For this purpose the heat developed in the outer conductor is assumed to be the same as that in the inner conductor.

* *Elektrotechnische Zeitschrift*, 1905, vol. 26, p. 137.

TABLE 28.

*Thermal Resistivities of the Dielectrics of Cables.**

Cable No.	Paper-insulated Cable		Mean Value of Thermal Resistivity in Electrical Measure, K	
	Sectional Area of Conductor, sq. in.	Working Pressure, volts	As determined	Values as Corrected after further Investigation
		Single Cables.		
1	0·1	660	1 200	—
2	0·2	660	800	—
		Concentric Cables.		
3	0·1	660	620	—
4	0·1	660	1 060	—
5	0·1	660	1 160	—
6	0·2	660	1 060	—
7	0·2	660	1 000	—
8	0·2	660	870 (jute insulated)	—
9	0·2	660	720	—
10	0·5	660	1 090	—
		Three-core Cables.		
11	0·025	660	1 050	1 330
12	0·05	11 000	730	—
13	0·1	6 600	720	775
14	0·1	660	670	—
15	0·1	6 600	420	—
16	0·15	6 600	500	—
17	0·15	20 000	460	505
18	0·15	20 000	550	600
19	0·15	20 000	470	527
20	0·15	20 000	550	618
21	0·15	20 000	460	515
22	0·15	20 000	570	640
23	0·2	20 000	600	648
24	0·2	20 000	600	648
25	0·2	3 300	650	—
26†	0·2	20 000	710	—
27	0·25	11 000	580	—
28	0·15	3 300	630	720
29	0·15	11 000	510	560
Bitumen filling			511	—
Paper (not impregnated) ..			960	—
Vulcanized bitumen			486	—
Vulcanized bitumen cables (value determined by Prof. Marchant)			510	—

* The dimensions of the cables are given in Appendix I.
† The inner and outer conductor of each core were in parallel and treated as one conductor.

quently used for 20 000-volt working. Further investigation has been directed to obtaining values that could be considered representative of modern cables for lower pressures. For this purpose, cables Nos. 28 and 29 were obtained, and the thermal resistivities of these cables were found to be 720 and 560 respectively. The manufacturer of cable No. 28 stated that he had purposely made a cable having a high value, since this would, and in fact did, provide an additional and interesting check on the methods of calculation. As a further example, a length of large three-core 660-volt cable had a value of approximately 750.

Examination of the experimental values for different types of cable showed that generally the lower-pressure cables had a thermal resistivity somewhat greater than the higher-pressure cables had. In view of the cost of manufacture it was considered unreasonable to expect that the lower-pressure cables would normally have a value of thermal resistivity as low as that of the higher-pressure cables, and therefore the following figures were adopted as representing fair values for the different types of cables.*

Cables for pressures up to and including 2 200 volts .. .. $K = 750$
Cables for pressures above 2 200 volts up to and including 11 000 volts .. .. .. $K = 550$

The value of K is obtained by means of the corrected Russell formula. If calculated by the uncorrected

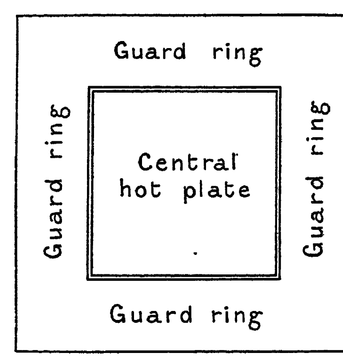

FIG. 3.—Diagram of apparatus for the determination of the thermal resistivity of soil.

formula as in the Preliminary Report the values are more nearly 700 and 500 respectively.

(3) THERMAL CONSTANTS OF THE SURROUNDING SOIL.

(*a*) *Thermal resistivity.*—Dr. E. Griffiths of the N.P.L. Heat Department has determined experimentally the thermal resistivity of soil with varying amounts of moisture content.

The apparatus consists of a flat central plate, electrically heated and surrounded by a guard ring (see Fig. 3). The guard ring consists of an outer plate in the form of a ring, in the same plane with the central plate but separate from it. The guard ring is main-

* Higher values have been adopted for cables with conductors having a sectional area less than 0·06 sq. in. to allow for the difficulty in manufacturing small cables.

tained at the same temperature as the central part, but the electrical power supplied to the central part is measured separately from that supplied to the guard ring.

At a distance of 1 in. from the hot plate were two other plates cooled by water circulation and maintained at a constant temperature.

Fig. 4 shows the apparatus before assembly; the hot plate with the guard ring is in the centre and the cold plates are on either side.

The soil was packed in wooden frames with zinc faces the size of the hot plate, and these were sealed in waxed paper envelopes. Thermo-couples of copper constantan were soldered to various points on the zinc faces. The frames were sandwiched between the hot and cold plates and surrounded with granulated cork.

The heat transmitted through the specimens was determined from observations of the watts dissipated in the hot plate. Before the final observations were taken, ample time was allowed for equilibrium to be attained, and the observations extended over a period of several days.

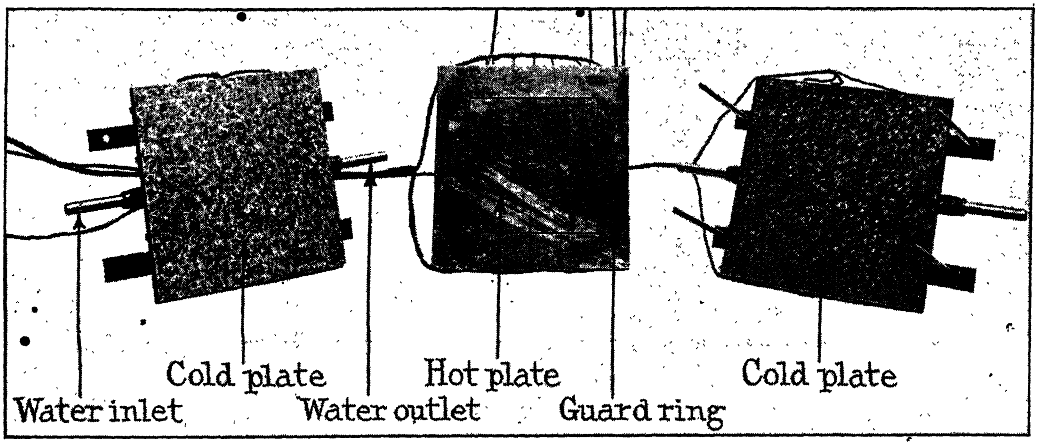

FIG. 4.—Apparatus for the determination of the thermal resistivity of soil.

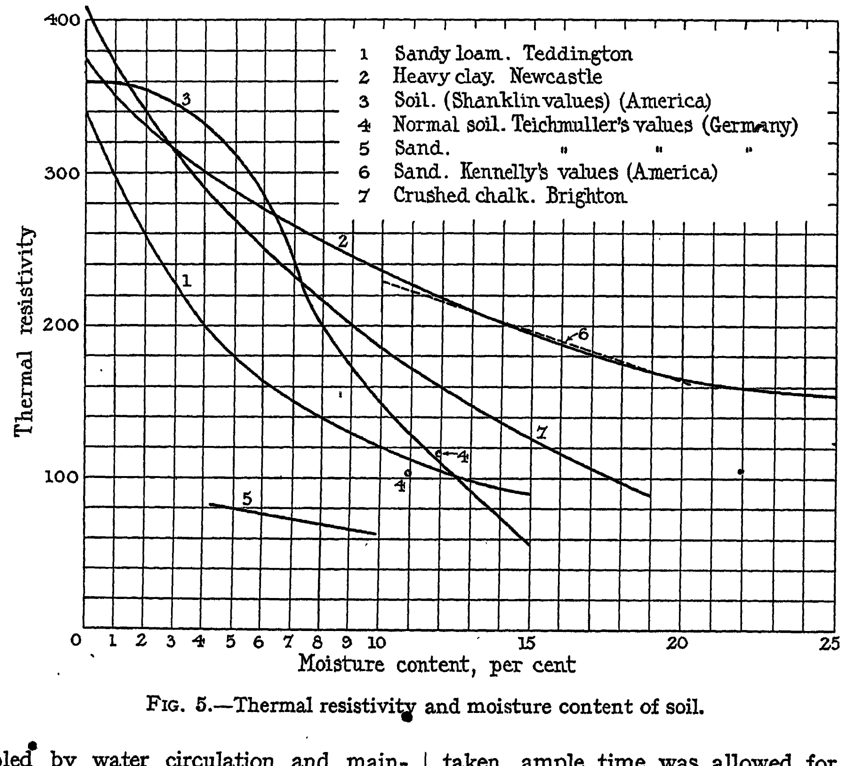

FIG. 5.—Thermal resistivity and moisture content of soil.

The range of temperature over which the test was made was from 15° C. to 25° C.; the temperature interval was kept as small as practicable in order to avoid disturbing unduly the distribution of moisture.

The resultant values are given in the curve shown in Fig. 5, which includes also values deduced from

Shanklin's results,* two values from Teichmüller and a curve from Kennelly's figures.

Two series † of observations were made at the N.P.L., one on the sandy loam soil of Teddington, and the other on heavy clay soil from the Newcastle district. It will be seen from Fig. 5 that the values for the two types of soil are markedly different; the clay is nearly the same as the sandy loam when both are dry, but it is considerably higher than the sandy loam when damp.

The N.P.L. values are quite regular, and the Shanklin curve for light soil agrees only at the extreme ends, the difference with moisture contents of from 1 per cent to 8 per cent being large. The two values of Teichmüller are near the point at which the N.P.L. and Shanklin curves cross, and are in fair agreement at this point. Kennelly's values for sand, however, agree closely with the N.P.L. curve for stiff clay.

(b) *Moisture content.*—The moisture content of the soil varies considerably from time to time and place to place. At Teddington in a normal year the moisture content varies from 9 per cent to 15 per cent, the latter figure being more usual during the winter. In the abnormal year of 1921 the values at 2 ft. depth taken at the N.P.L. are given in Table 29.

TABLE 29.

Moisture Content of Soil at Teddington in 1921 *and* 1922.

Date	Moisture Content, per cent
8th July, 1921	4·5
20th November, 1921 ..	8·0
12th January, 1922 ..	14·0
22nd April, 1922 ..	12·0

Observations taken by Mr. M. Farrer, Engineer and Manager to the Twickenham and Teddington Electric Supply Co., showed that in the neighbourhood of Teddington the values were from 10 per cent to 14 per cent up to June 1921, but that at Claygate, a few miles away, where the soil is clay and the height above sea level much greater than at Teddington, at one place the exceptionally low values of from 1·6 per cent to 2·8 per cent were obtained in November 1921.

These low values are apparently not due to drying of the soil by the heat from the cable, since in one case in which observations were taken the moisture content immediately against the cable was 2 per cent, and at 18 in. away from it was 1·9 per cent.

In the Newcastle-upon-Tyne district the figures for the latter part of 1920 showed that the moisture content varied from 14 per cent to 38 per cent, the more general value being about 20 per cent. From April to June 1920 the values varied from 8 per cent to 39 per cent. For 1921, the values varied from 4 per cent to 28 per cent. Other towns show differences of much the same order. The late Mr. G. L. Black obtained values at Glasgow in 1920 varying from 11 per cent to 29 per cent, and the values obtained by Mr. J. Christie at Brighton in 1921 varied from 15 per cent to 21 per cent.

In Buenos Aires, during May and June 1921, Mr. J. Wilson determined the moisture content at 20 different places, and the values varied from 16 per cent to 28 per cent, the average being 21·4 per cent.

The statement given above is a short summary of the overall limits of the values observed. It will be appreciated that the moisture content will vary with different types of soil, and with climatic conditions, and that where cables are being run continuously at approximately the maximum current-loading, observations should be made of the moisture content with a view to ascertaining the minimum to be expected under full-load conditions. This is particularly necessary where cables are laid close to the surface and where the moisture content would probably be lower than at a greater depth. A large number of observations has been made, and while it is clear that it is impossible to provide data capable of general application, the series of observations taken in the Newcastle-upon-Tyne district are given in Appendix V for the purpose of showing the order of variation that might be expected both at different times of year and in various types of soil at the same time.

Engineers have from time to time drawn attention to the drying action of a heated cable, and have stated that with a continuously loaded cable the soil in the immediate vicinity becomes quite dry; but although in the course of the investigation definite evidence on this point has been sought, it has not been obtained.

It is extremely rare for soil to have a less moisture content than 5 per cent, even when appearing to be quite dry. Moreover, practical tests have shown that the soil immediately surrounding a cable running continuously on full load for a week was distinctly wetter than that at distances of 1 and 2 ft. away horizontally, values of moisture content of 18, 16 and 14 per cent respectively being obtained. These values occurred in open country in stiff clay at several points that had not been disturbed previously for 12 years. It is common experience to find the cable trench many years after excavation acting as a drain to the surrounding country.

When cables are required to be loaded for long periods at their maximum current, attention should be paid to the condition of the soil in view of the large difference in current-carrying capacity for the extremes that may be met with.

It was decided: (1) To adopt the series of values connecting moisture content and thermal resistivity obtained at the N.P.L., and (2) to prepare four sets of tables of maximum permissible currents for armoured cables laid direct in the ground, and values for armoured and unarmoured cables in air, and for unarmoured cables drawn into ducts.

It was also decided that the current-loadings in the four sets of tables for armoured cables laid direct in the ground should correspond to the values of moisture content and thermal resistivity of the soil given in Table 30.

In the case of heavy clay soil with moisture content greater than that given above, the value of the thermal

* *Journal of the American Institute of Electrical Engineers* 1922, vol. 41, p. 92.
† For values for chalk see Appendix VIII.

resistivity is not reduced appreciably; for instance, with a moisture content of 25 per cent the thermal resistivity is approximately 150 (see Fig. 5).

(*c*) *Depth of laying*.—The experimental work to determine the effect of the depth of laying, published in the Preliminary Report, has been compared with theoretical formulæ. In the experimental work three lengths of 0·1 sq. in. three-core 660-volt cable were laid at Newcastle-upon-Tyne at depths of 1·5, 2·5 and 4·5 ft. respectively, and the heating was determined.

The general formula shows the importance of the term G, the thermal resistance of the ground. The question of the depth of laying is therefore intermixed with the question of the validity of the assumption regarding the heat flow, but in order to show more clearly the comparison between experimental and calculated results, the question of the depth of laying may be considered here, comparing the values obtained with those calculated by means of the formula finally adopted.

TABLE 30.

Values of Thermal Resistivity and Moisture Content of Soil on which the Current-loading Tables are based.

Thermal Resistivity of Soil, g	Approximate Moisture Content of Soil		
	Sandy Loam	Heavy Clay	Chalk
340	0	1 %	2 %
180	5 %	17 %	10 %
120	10 %	—	16 %
90	15 %	—	20 %

The heating of a buried cable is governed by the relation—

$$H = t/(G + S) \quad . \quad . \quad . \quad . \quad (26)$$

where H = total heat in watts developed in each cm length of each conductor.

t = temperature-rise of the conductor above the datum level.

S = thermal resistance of the dielectric and the protective coverings surrounding the conductor.

G = thermal resistance of the earth between the protective covering of the cable and the external isothermal.

For a cable of the type considered, S is approximately 35 and the three values of

$$G = \frac{g}{2\pi} \log_e \left(\frac{2L}{r_6}\right) \quad . \quad . \quad . \quad . \quad (27)$$

corresponding to the three depths of laying specified, are as follows:—

For $L = 1{\cdot}5$ ft., $G = 54{\cdot}0$.
„ $L = 2{\cdot}5$ ft., $G = 60{\cdot}5$.
„ $L = 4{\cdot}5$ ft., $G = 68{\cdot}0$.

Comparing first the experimental results obtained, the average increase in temperature-rise in a cable laid at 2·5 ft. below the surface of the ground was 4 per cent (the mean of a series of values ranging from 0·7 to 7·4 per cent) over that of a similar cable carrying the same current and laid at 1·5 ft. below the surface.

According to the general formula, the ratio of temperature-rise in the two cases is given to a first approximation by the equation—

$$\frac{t}{t'} = \frac{S + G'}{S + G} = \frac{35 + 60{\cdot}5}{35 + 54{\cdot}0} = 1{\cdot}07 \quad . \quad (28)$$

or the temperature-rise at 2·5 ft. is 7 per cent greater than at 1·5 ft.

The average increase of temperature-rise in a cable laid at 4·5 ft. below the surface was 15·7 per cent over that of a similar cable carrying the same current laid at 1·5 ft. This was the mean of a series of results ranging from 10·8 to 18·95 per cent.

The calculated value for this case is

$$\frac{t}{t'} = \frac{35 + 68}{35 + 54} = \frac{103}{89} = 1{\cdot}16$$

In computing the current-loading tables it was decided to adopt 18 in. as the depth of laying for cables for pressures up to and including 2 200 volts, and 3 ft. for cables for pressures above 2 200 volts up to and including 11 000 volts, the dimension being in each case the distance from the surface of the ground to the axis of the cable.

(4) TEMPERATURE OF THE GROUND.

A large amount of information has been collected on the actual temperature of the ground in different parts of the world. For Britain, full information is available in the reports of the Meteorological Office, and these are shown in Fig. 6. The values for Calcutta and various parts of Australia, which have been furnished through Mr. B. Welbourn, are shown in Figs. 7, 8, 9, 10 and 11.

It will be seen from Fig. 6 that even in the abnormal year of 1921 the maximum ground temperature at a depth of 2 ft. was only approximately 20° C. and that during the greater part of the year the value was lower than 15° C. (the Australian figures are not greatly higher than these).

It was appreciated that the highest ground temperature coincided with the period when the peak load would be in general a minimum, and it was decided to adopt a value of 15° C. as representing the average temperature on which current-loading tables should be based.

(5) EXPANSION OF CABLES.

The extent to which the conductor and the lead sheath of a cable expand is a factor which requires consideration in connection with current-rating. The total expansion as a result of heating may be taken up in various directions, but the differential expansion between the lead and the copper gives an indication of the internal stresses to which the cable is subjected.

The expansion that would be expected can be calculated from the coefficient of expansion of the materials and from knowledge of the temperature. Taking the following coefficients:—

For copper	.. ..	0·0000168 for 1 degree C.
For lead	.. ..	0·0000275 „ „

and taking values of temperature from actual observations in which the rise of temperature of the lead sheath is about one-half that of the conductor, the expansion per 100 yards' run after steady conditions have been reached in a cable as used for 20 000 volts is as follows:—

Conductor ..	0·6 in. for 10 degrees C. temperature-rise of conductor.
Lead sheath..	0·47 in. for 10 degrees C. temperature-rise of conductor.

For an 11 000-volt cable:—

Conductor ..	0·6 in. for 10 degrees C. temperature-rise of conductor.
Lead sheath..	0·58 in. for 10 degrees C. temperature-rise of conductor.

the difference of temperature between the conductor and the sheath might be greater than when the steady condition is reached. As a further example, therefore, a 0·15 sq. in. 11 000-volt cable laid direct in the ground was tested 2 hours after the current (220 amperes) had been switched on, and the results were as follows:—

Temperature-rise of lead sheath ..	8 degrees C.
Temperature-rise of conductor ..	18 degrees C.

Under these conditions the calculated

Expansion of 100 yards of conductor would be 1·09 in.

Expansion of 100 yards of sheath would be 0·74 in.

It is apparent, however, that with an armoured three-core cable in which the cores are twisted around each other the linear expansion is considerably less than the

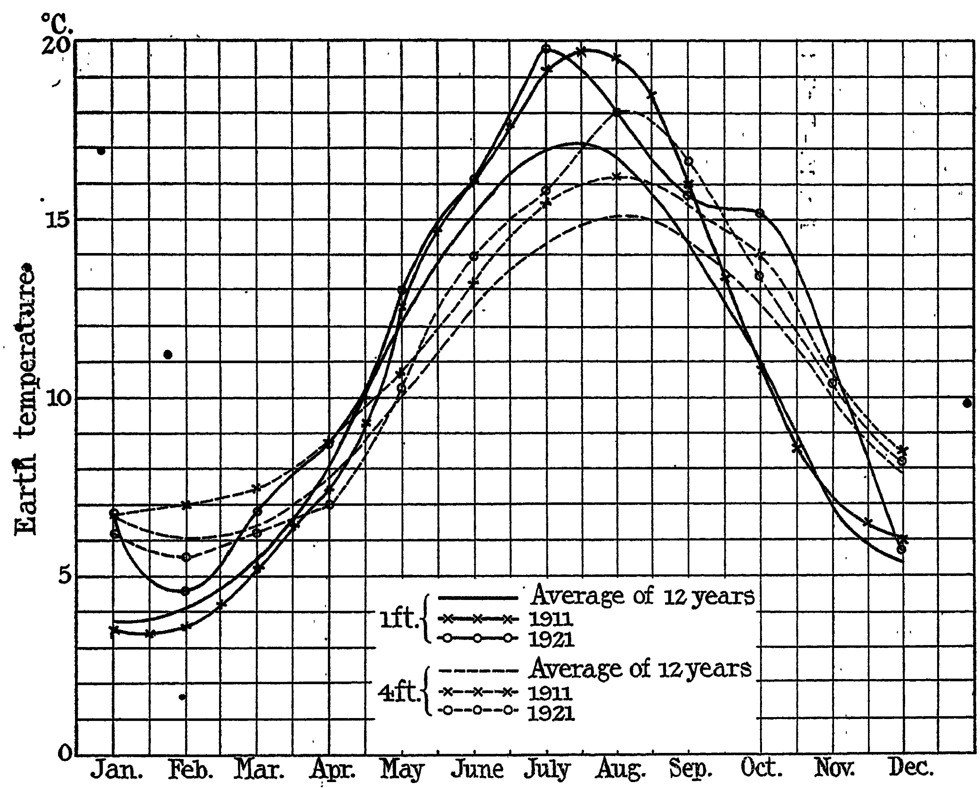

FIG. 6.—Earth temperatures at Kew.

For a 3 300-volt cable:—

Conductor ..	0·6 in. for 10 degrees C. temperature-rise of conductor.
Lead sheath..	0·56 in. for 10 degrees C. temperature-rise of conductor.

Thus in these examples the differential expansion is small, the difference of temperature between conductor and sheath being compensated for by the difference in the coefficient of expansion.

It appeared to be possible that the conditions of continuous loading did not necessarily represent the most severe conditions, since in the early part of the heating above values would indicate. Some tests by a large firm of cable makers gave results which, when reduced to a basis comparable with the above, are as follows:—

For a 0·15 sq. in. three-core high-voltage armoured cable laid out along a floor:—

Temperature-rise of conductor ..	40 degrees C.
Temperature-rise of sheath ..	20 degrees C.
Differential expansion between conductor and sheath ..	0·024 in.
Differential expansion between sheath and ground	0·9 in.

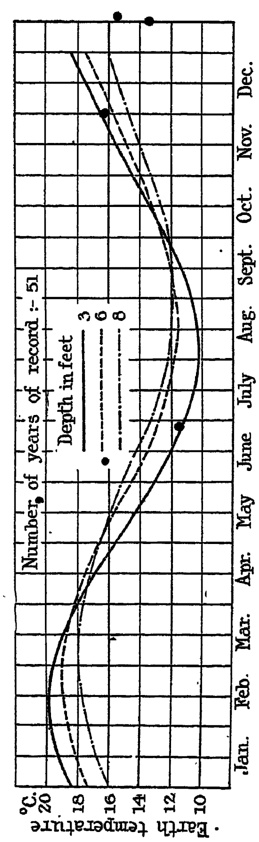

FIG. 7.—Earth temperatures at Melbourne (Australia).

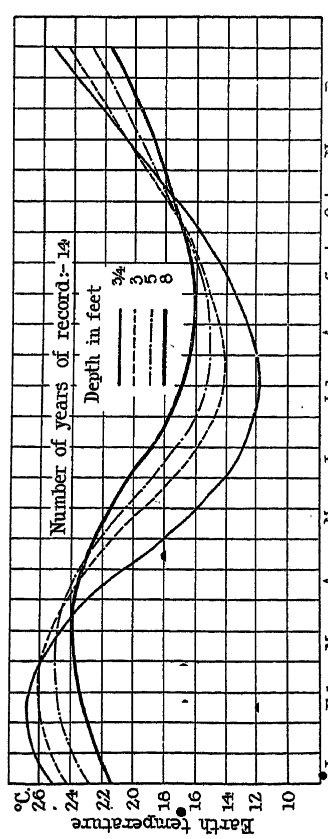

FIG. 8.—Earth temperatures at Perth (Australia).

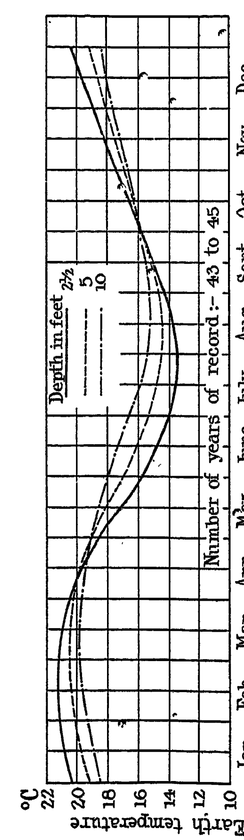

FIG. 9.—Earth temperatures at Sydney (Australia).

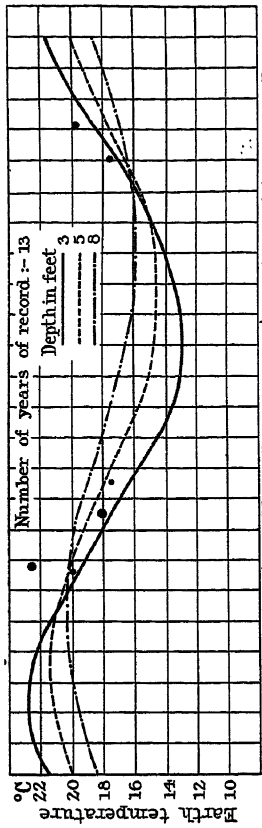

FIG. 10.—Earth temperatures at Adelaide (Australia).

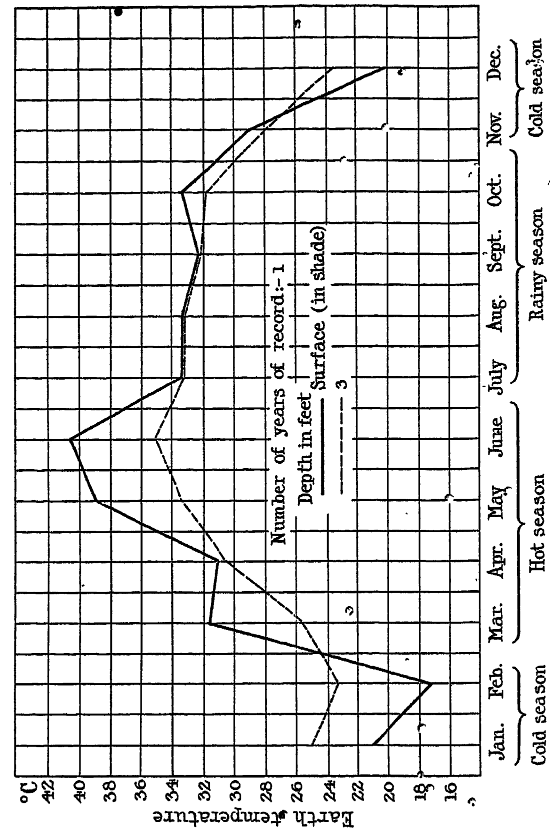

FIG. 11.—Earth temperatures at Calcutta (India).

Had the lead and copper expanded freely the expansion would have been :—

Copper	=	2·35 in.
Lead	=	2·0 in.
Armouring	=	0·9 in.

The conclusion drawn was that the copper and lead expanded by the amount of the expansion of the armouring only, the frictional grip of the paper around the copper and that of the armouring around the lead and the paper under the lead being sufficient to prevent any further expansion.

The lead and copper therefore will be in a state of longitudinal compression and the resultant expansion may be radial.

Apart from the temporary expansion, results of actual measurements by Beaver * indicate that after a cable has been heated and cooled a permanent set is produced, the amount and direction of which varies in different parts of the cable. A result of this kind may apply only to the exact condition under which the particular tests were made and does not necessarily hold for all conditions of laying; at the same time, however, the values obtained are of great interest and significance.

(6) Maximum Permissible Temperature for Paper-insulated Cables for Pressures up to and including 11 000 Volts.

The question as to the maximum temperature to which the impregnated paper dielectric can be exposed for long periods without fear of deterioration, either mechanical or electrical, is one on which various authorities are somewhat in conflict. The present permissible temperatures for various countries are as follows :—

(1) American (I.E.E.) .. .. 85° C., less 1 degree C. for each 1 000 volts increase.
(2) German (V.D.E.) .. .. 50° C.
(3) French (Laboratoire Central) 50° C.

In 1921 the following figures were suggested by various American investigators ** :—

(4) Del Mar † .. .. .. 85° C. to 90° C.
(5) Elden ‡ .. .. .. 85° C.
(6) Torchio § .. .. .. 105° C. to 110° C.
(7) Fisher and Atkinson ‖ .. 85° C.
(8) Roper ¶ .. .. .. 110° C.

These later values are all based on consideration of the mechanical properties of the paper only, and from this point of view alone the suggested limit of 80° C. to 85° C. is probably quite reasonable, and is confirmed by the preliminary experiments at the National Physical Laboratory published in the Preliminary Report.

In June 1922, Roper published results ¶ showing that at the normal operating temperature a large number of breakdowns occurred on cable systems, apparently due mainly to heating in the dielectric.

The German values are based on the dielectric losses, 50° C. being the point at which according to their earlier investigations these losses become appreciable. Considerable improvement has been effected in recent years in this respect and it appeared probable on the information available that from the point of view of the dielectric only a temperature of 80° C. might be adopted, especially as the dielectric losses of the cables dealt with in the current-loading tables are so small that they can be neglected.

After full consideration of all the various factors involved it was decided to adopt 65° C. (that is allowing a rise of temperature of 50 degrees C. above the value of 15° C. taken as the normal temperature of the ground) for the maximum temperature of the conductor for armoured cables up to and including 11 000 volts working pressure, laid direct in the ground. Here emphasis has been laid on the heavy cost of replacing underground mains and the long life and reliability of operation which are required for such cables. Moreover, it was appreciated that :—

(*a*) There was danger of mechanical trouble with an excessive temperature owing to the movement of the cable relative to the earth or duct.

(*b*) For the higher-pressure cables it was desirable to err on the side of safety, while for the lower-pressure cables it would not be economical to run at high temperatures, since owing to the operation of Kelvin's law the cost of the energy losses would be in excess of the saving in copper.

The actual difference in permissible current-loading between rises of 50 degrees C. and 65 degrees C., corresponding to final temperatures of 65° C. and 80° C. respectively, is approximately 12 per cent.

In view of the fact that a cable drawn into a duct is free to move lengthways along the duct and cause injury to the lead by abrasion, it was considered that the permissible temperature should be lower than that for cables laid direct in the ground. It was decided, therefore, to adopt 50° C. for the maximum temperature of the conductor for plain lead-sheathed cables drawn into ducts, this value corresponding to a temperature-rise of 35 degrees C.

(7) Summary of Proposed British Constants and those adopted by Other Countries.

In Table 31 is given a summary of the various constants now proposed, as the result of this investigation, for the calculation of current-loading tables. The corresponding constants adopted by the French, German and Japanese authorities are given for comparison.

British: Values refer to one cable. It is recommended that where two cables are laid in the same trench and in the same horizontal plane the current should be reduced in the following ratios (see Table 37, page 549) :

Four inches between axes	.. 0·76
Eight inches between axes	.. 0·82
Twelve inches between axes	.. 0·86

French: Values refer to one cable. It is recommended that where more than one cable is laid in the

* *Journal I.E.E.*, 1915, vol. 53, p. 57.
** See Addendum on page 561.
† *Journal of the American Institute of Electrical Engineers*, 1921, vol. 40, p. 131.
‡ *Ibid.*, 1921, vol. 40, p. 145.
§ *Ibid.*, 1921, vol. 40, p. 96.
‖ *Ibid.*, 1921, vol. 40, p. 183.
¶ *Ibid.*, 1921, vol. 40, p. 201.

same trench the current should be reduced in the following ratios :—

Two cables	0·84
Three cables	0·76
Larger number	0·55

German: Values refer to two cables laid in the same trench.

(8) Representation by General Formula.

The calculation of the temperature-rise of a buried cable is based upon the relation :—

$$H = t/(S + G) \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

The calculation of the thermal resistance S in the case of a single conductor is

$$S = \frac{K}{2\pi} \log_e \left(\frac{r_4}{r_1}\right) \quad . \quad . \quad . \quad . \quad . \quad (30)$$

Russell's formula for the thermal resistance of unit length of a multi-core cable is :—

$$S = \frac{K}{2\pi n} \log_e \frac{(r_4^{2n} - a^{2n})}{n r_4^n a^{n-1} r} \quad . \quad . \quad . \quad . \quad (33)$$

Various suppositions have been made regarding a suitable expression for G, the thermal resistance of the soil surrounding the cable. Kennelly * supposed that the surface of the ground above the cable might be regarded for practical purposes as a plane isothermal. On this supposition, applying the method of electrical images as in Foster and Lodge's paper (*Philosophical Magazine*, 1875) it can be shown that

$$G = \frac{g}{2\pi} \log_e \left\{ \frac{2l}{2r_6} + \sqrt{\left(\frac{l^2}{r_6^2} - 1\right)} \right\} \quad . \quad . \quad (34)$$

TABLE 31.

Summary of Proposed British Constants and those Adopted in the Calculation of Foreign Current-loading Tables.

Constants	British (now proposed)		French	German	Japanese
	Laid Direct in the Ground	Drawn into Ducts			
Permissible temperature-rise of conductor	50 deg. C.	35 deg. C.	40 deg. C.	25 deg. C.	85 deg. C.
Maximum permissible temperature	65° C.	50° C.	50° C.	50° C.	100° C.
Temperature of soil	15° C.	15° C.	10° C.	25° C.	15° C.
K of soil	340, 180, 120 and 90	—	200	100	324‡
K of cable	550 and 750	550 and 750	230*	500†	636
Depth of laying	1 ft. 6 in. and 3 ft.	—	Not specified	2 ft. 3 in.	3 ft.

* The very low value here is not the result of experiment, but appears to have been adopted after examination of the values given by various investigators. It would seem probable that there is an error in the French values due to a misunderstanding as to the units in which the thermal resistivity is expressed.

† This corresponds to the British value of 550.

‡ Dry sand.

The same formula applies to the external armouring when this is present, the thermal resistance being then the sum of two such terms, so that

$$S = \frac{K}{2\pi} \log_e \left(\frac{r_4}{r_1}\right) + \frac{K'}{2\pi} \log_e \frac{r_6}{r_5} \quad . \quad . \quad . \quad (31)$$

The thermal resistance of the lead sheath is regarded as negligible. In the concentric cable the thermal resistance between the conductors and the sheath, the thermal resistance of the outer conductor being neglected, is given by the formula :—

$$S = \frac{K}{2\pi}\left[\tfrac{1}{2} \log_e \left(\frac{r_2}{r_1}\right) + \log_e \left(\frac{r_4}{r_3}\right)\right] \quad . \quad . \quad (32)$$

In the case of a multi-core cable two or three different formulæ are available for the calculation of the thermal resistance from the thermal resistivity, or vice versa. These are fully dealt with in the section on page 565.

Here l is very closely the depth of the cable axis below the surface of the ground, and for the purposes of this investigation $l = L$.

Usually l^2/r_6^2 is large compared with unity. For example, taking $l = 18$ in. and $d = 3$ in., $l^2/r_6^2 = 144$. The expression for G can therefore be simplified and written in the form

$$G = \frac{g}{2\pi} \log_e \left(\frac{2L}{r_6}\right) \quad . \quad . \quad . \quad . \quad . \quad (35)$$

In this form it was used by Teichmüller and others (see "Die Erwärmung der Electrischen Leitungen," p. 53).

The basic assumption here is that the surface of the earth above the cable, because of the free dissipation of heat due to radiation and convection through the ambient air, forms an isothermal surface, and this henceforward will be referred to as the Kennelly assumption.

* *Electrical World*, 1893, vol. 22, p. 183.

Other and simpler assumptions have been proposed by various investigators, e.g. that due to Apt, references to which occur in other parts of this report. Apt suggested that as a first approximation the effect of the earth surrounding the cable should be considered to be equivalent to that of a cylinder of material equal in thermal resistivity to the soil and having a radius equal to the depth of the cable axis below the surface of the ground. On this assumption,

$$G = \frac{g}{2\pi} \log_e \left(\frac{L}{r_6}\right) \quad . \quad . \quad . \quad . \quad . \quad (36)$$

The heat generated, $H = nI_2R_1$ . . . . (37)

where I = current.

n = number of conductors.

$R_1 = R(1 + 0{\cdot}004\ t)$, the resistance in ohms per cm of the cable at working temperature, taking the temperature coefficient of copper as 0·004.

The formula for the determination of the current to produce a given temperature-rise of the conductor t_1 is therefore

$$I = \frac{1}{\sqrt{[nR(1 + 0{\cdot}004\ t_1)]}} \sqrt{\left(\frac{t_1}{S + G}\right)} \quad . \quad (38)$$

It was considered, however, that the assumptions regarding the heat-flow through the surrounding soil were not justified, and an attempt has therefore been made to determine experimentally the actual shape of the isothermals surrounding a buried cable. Kennelly and Teichmüller assumed that the boundary of the earth and air formed an isothermal plane, but practical experience suggested this was not strictly accurate, as cases are well known of the route of a heavily loaded cable being clearly traceable by the drying of the surface of the soil immediately over it, which suggested a higher temperature of the ground surface immediately above the cable.

Previous work on buried cables had shown that many variable factors existed and that tests made on ordinary soil would probably be seriously influenced by

(*a*) Lack of homogeneity.
(*b*) Change in moisture content with position and time.
(*c*) Inconstant weather conditions.

The test to be made had therefore to be under cover—

(*a*) In homogeneous material.
(*b*) Of constant moisture content.
(*c*) In practically still air at a reasonably constant temperature.

The question of the best material to use was considered at length, and the relative advantages and disadvantages of bitumen, dry sand and other materials were reviewed, which resulted in sand being chosen, chiefly because of the elaborate precautions necessary with bitumen and allied compounds to prevent displacement of the measuring thermo-couples during shrinkage on cooling.

The test was made on as large a scale as practicable, a rectangular box, 3 ft. square and 4 ft. 6 in. high, being built strong enough to contain 2 tons of specially dried sand. For the first test, the conductor was a metal tube 0·7 in. external diameter placed vertically in the box on one centre line, 1 ft. from one boundary. This gave a ratio of 35 for the depth of laying to the radius of the cable, a very similar value to that assumed by Teichmüller.

The measurement of temperature distribution was made by means of 40 specially constructed thermo-couples standardized by the National Physical Laboratory, the hot junctions lying in a horizontal plane half-way up the box, the thermo-couple wires being stretched vertically so as not to disturb the lines of heat-flow. These thermo-couples were arranged on lines radial

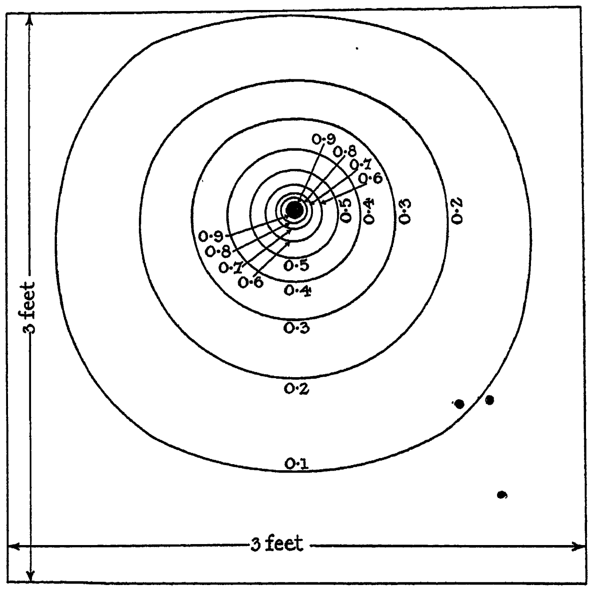

FIG. 12.—Isothermals in dry sand.

from the conductor and as accurately positioned as possible. The sand was then gently sifted in until the box was full, and, after settling down, the thermo-couples were checked.

The current was set to maintain a temperature-rise of 55 degrees C. and this current corresponded to 7·7 watts per foot run. Conditions were maintained as steady as possible for one week, when readings at all the thermo-couples were taken, from which the chart shown in Fig. 12 was plotted. A further set of readings one week later were in substantial agreement.

The cylindrical surface corresponding to the relative temperature-rise (1·0) coincides with the outer surface of the cable, and the other isothermals are decimal parts of this down to 0·1. As the boundaries of the sand in this test were in no direction very much greater than the depth of laying, it was considered of interest to make a further test with those boundaries relatively much further off. This was done by sinking a new conductor 3 in. from one boundary, on the same centre line as the metal tube. The diameter of this conductor

was chosen to give the same ratio (35) as before. The thermo-couples were not quite so satisfactorily placed for this test, but they could not, of course, be disturbed; their position was accurately known, and it was possible to draw a temperature distribution chart in this case also (see Fig. 13). The temperature-rise was as before, corresponding to 6·55 watts per foot run, and readings were taken after the current had been maintained for one week.

In this chart (Fig. 13) the isothermals above 0·5 are omitted for clearness, as they are evidently circles nearly concentric with the conductor, but all the isothermals for 0·15 and below cut the ground boundary.

These results indicate that the assumptions regarding the lines of heat-flow do not correspond to the observed facts, and, as will be shown later, it is necessary to modify one of the terms of the formula in order to obtain satisfactory agreement between experimental and calculated values.

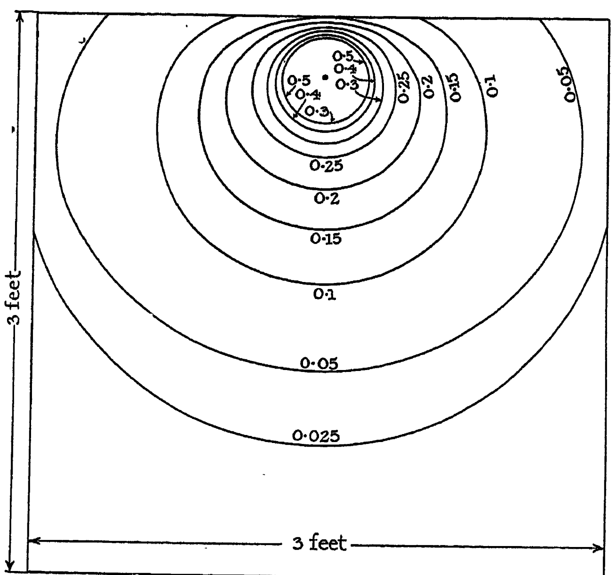

FIG. 13.—Isothermals in dry sand.

In the calculation of the German tables the V.D.E. Commission adopted a formula based upon Kennelly's assumption, but took the thermal resistivity of the ground as being one-half the actual value. The reason for this was not apparent until experimental results were obtained which showed that Kennelly's assumptions could not be altogether justified. It may therefore be inferred that the reduced value was taken to meet the discrepancy between calculated and experimental values. As an alternative method of reconciling the two sets of values a formula based on Apt's assumption was also considered. Here in place of Kennelly's assumption that the surface of the ground is an isothermal it is supposed that the isothermal surfaces are concentric with the cable, and that the total effect of the earth around it is somewhat arbitrarily regarded as being equal to that of surrounding the cable with a cylinder of earth, the radius of which is equal to the depth of the cable axis below the surface of the ground.

The cables actually tested when buried direct in the ground cover a very wide range of cable sizes, and have been under observation at different periods of the year and under widely different conditions of soil temperature, resistivity, etc. It therefore becomes possible to compare the experimental values for the whole series with existing values, and to consider the modification of the general formula necessary for the calculation of the current-rating of various sizes and types of cables. For the purpose of the comparison the more important factors, such as the moisture content of the soil, have been determined at frequent intervals and the values corrected to a standard value of thermal resistivity of the soil. Also the thermal constants of all the cables have been fully determined, both when in air and buried in the ground, and the effect of armouring has been investigated.

In order to make an effective comparison not affected by small variables in any particular cable the experimental values have been corrected to a common basis, and those given in Table 32 refer to the following conditions:—

(*a*) The dimensions of the cable are exact.
(*b*) The conductor resistance is of standard value.
(*c*) The thermal resistivity of the dielectric is 550 for cables for pressures above 2 200 volts and 750 for cables for pressures up to and including 2 200 volts.
(*d*) The thermal resistivity of the armouring is 300 (this is the average value of all the cables measured at the N.P.L.).
(*e*) The thermal resistivity of the soil is 120.
(*f*) The value of current is that required for a rise of temperature of the conductor of 50 degrees C.

A comparison with the latest V.D.E. tables is given in Table 32.

There are, however, the following important differences between the two sets of values:

(1) Thermal resistivity of the soil. In the German case this is taken as 50, while in the present investigation the value is 120.
(2) The V.D.E. tables refer to two cables run in the same trench; the distance apart is not stated. For comparison, therefore, the experimental values are given both for one cable and for two laid in the same trench, at 4 in. and 8 in. apart respectively between axes. The thermal resistivity K of the cable is in each case 550, corresponding to 500 when calculated by the uncorrected formula.

In Table 33 a comparison is given of the experimental and calculated values of maximum permissible currents; in the latter the Kennelly and Apt assumptions are both used in each case for two values of g.

If an intermediate value of $g = 80$ be taken then on the Kennelly assumption, the values given in Table 34 are obtained. Values based on the Apt assumption are in equally good agreement as a series for one particular depth of laying. But the experimental determination of the effect of depth showed that the Kennelly assumption more nearly represented the facts, and therefore

the formula based on this assumption has been used with the necessary corrections.

The agreement between the experimental and the calculated values given in Table 34 was considered to be remarkably good, and proved that the method of calculation used was sufficiently close for all practical purposes. The complete current-loading tables, therefore, were calculated on the Kennelly assumption, corrected in accordance with the experimental results (i.e. by taking g' as two-thirds of g).

TABLE 32.

Currents required to cause a Temperature-rise of 50 deg. C. in Armoured Cables laid Direct in the Ground.

Size and Type of Cable	Working Pressure, volts	Current in Amperes for a Rise of 50 deg. C.			
		Experimental Values corrected to a Common Basis of $g = 120$			V.D.E. Tables, $g = 50$
		One Cable	Two Cables		Two Cables in One Trench
			4 in. Apart	8 in. Apart	
All Armoured :					
0·1 sq. in. concentric ..	660	280	213	230	282
0·2 sq. in. concentric ..	660	419	318	345	440
0·15 sq. in. 3-core	3 300	295	224	243	331
0·15 sq. in. 3-core	11 000	288	219	237	310
0·15 sq. in. 3-core	20 000	283	—	—	—

TABLE 33.

Comparison of Experimental and Calculated Values of Maximum Permissible Currents.

Size and Type of Cable	Working Pressure	Corrected Experimental Values, $g = 120$	Calculated Values			
			$g = 120$		$g = 60$	
			Kennelly	Apt	Kennelly	Apt
All Armoured :	volts	amps.	amps.	amps.	amps.	amps.
0·1 sq. in. concentric ..	660	280	257	273	313	327
0·2 sq. in. concentric ..	660	419	372	395	454	475
0·15 sq. in. 3-core	3 300	295	258	274	308	321
0·15 sq. in. 3-core	11 000	288	257	286	302	314
0·15 sq. in. 3-core	20 000	283	261	276	309	321

TABLE 34.

Comparison of Experimental and Calculated Values of Maximum Permissible Currents.

Size and Type of Cable	Working Pressure	Corrected Experimental Values, $g = 120$ (1)	Calculated Values, $g = 80$ (2)	Ratio (2)/(1)
All Armoured :	volts	amps.	amps.	
0·1 sq. in. concentric	660	280	291	1·04
0·2 sq. in. concentric	660	419	421	1·00
0·15 sq. in. 3-core	3 300	295	288	0·98
0·15 sq. in. 3-core	11 000	288	284	0·98
0·15 sq. in. 3-core	20 000	283	289	1·02
			Mean	$1{\cdot}00_4$

(9) THREE-CORE CABLES USED ON THREE-WIRE CIRCUITS.

The possible increase of current when a three-core cable is used on a three-wire circuit, the third conductor carrying the out-of-balance current only, has been considered. It is clear that since any out-of-balance current flowing through the third conductor will reduce that in one of the other two by an equal amount, the balanced-load condition is the least favourable from the point of view of temperature-rise. This condition, therefore, has been assumed in the consideration of the problem.

Actual experiments were made with two three-core cables, one a very large 660-volt cable, and the other a 2 200-volt cable, and it was found that in the first case the ratio of the currents to produce the same temperature-rise of the conductor was 100 to 117. The size of the second cable was 0·25 sq. in., and here the ratio of the currents was 100 to 118. These two cables

represent a considerable diversity in the ratio of diameter of conductor to thickness of dielectric and, therefore, it can be fairly assumed that the ratio of currents will hold for all sizes of cables.

A determination of the thermal resistance of a three-core cable with only two cores energized was also made by means of the electrostatic method described before. With two conductors only connected, the third being idle, the capacity of a model corresponding to the dimensions of a cable was 191 $\mu\mu$F, and with the three conductors connected the capacity was 232 $\mu\mu$F; the thermal resistance of a cable under these conditions will be in the ratio of the reciprocals of these two values.

If the method is applicable to such a condition the total power dissipated in the cable for a given temperature-rise should be proportional to the capacities. Taking 100 to 117 as the ratio of the current as determined by experiment, since three conductors are carrying current in the one case and two in the other, the power dissipated corresponds to $(100^2 \times 3)/(117^2 \times 2)$, which is proportional to 91/100. The value obtained for one arrangement of the electrostatic model corresponds to 232/191, which is proportional to 100/82; and the value for the other arrangement of the electrostatic model corresponds to 171/136, which is proportional to 100/80.

Thus there is a discrepancy of about 10 per cent between the two methods, and it would appear that the electrostatic method does not apply when two conductors only are carrying current.

(10) Four-core Cables.

In the case of four-core cables in which three cores only are energized, the fourth carrying any out-of-balance current, it follows that the values will be very nearly the same as for three-core cables with each core equally loaded. It has been shown by comparison of the heating of a three-core cable with two and three cores energized, that the total power in the cable for a given temperature-rise is only decreased by 10 per cent when two cores are energized.

Apart from the fact that the difference between two and three cores is greater than that between three and four, the basis of comparison is much more extreme, since in the one case the heating of three energized cores is compared with that of two energized cores, while in that now under consideration three cores are always energized, the only difference being the interposition of a fourth core which normally carries little or no current. Since in the extreme case mentioned above the difference was only 10 per cent it may be safely assumed that the rating for a four-core cable will be the same as for a three-core.

An experiment on a length of four-core 0·05 sq. in. 660-volt armoured cable showed that when the four conductors were carrying current the power dissipated for a given temperature-rise was only 3·3 per cent more than when three conductors only were carrying current. This test confirms the conclusion reached that for practical purposes the current-rating of a four-core cable, in which the fourth core carries the out-of-balance current, is the same as that for a corresponding three-core cable.

(11) Triple-concentric Cables.

In the case of triple-concentric cables used on a three-wire system, and assuming the load to be balanced and carried by the two inner conductors, and taking the thicknesses of the dielectric as specified in B.S.S. No. 7—1922, the current for a given temperature-rise would be 5 per cent less than that for the equivalent size of concentric cable with two conductors only.

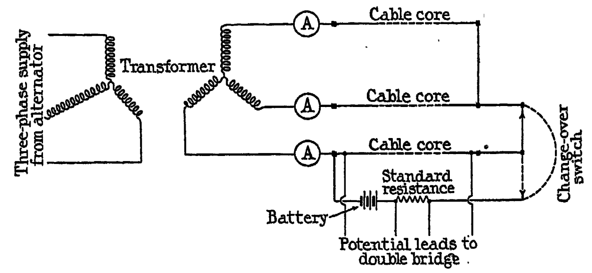

Fig. 14.—Diagram of connections for three-phase loading.

(12) Cables for Pressures above 11 000 Volts.

It was decided that it would be preferable to defer the preparation of current-loading tables for cables for pressures above 11 000 volts until the complete results of the dielectric-loss tests were available, and that for the present the tables should apply to the sizes and types of cable in general use given in British Standard Specification No. 7—1922.

A great deal of work has been done on cables for pressures above 11 000 volts, but this will form the subject of a further report when this section is completed.

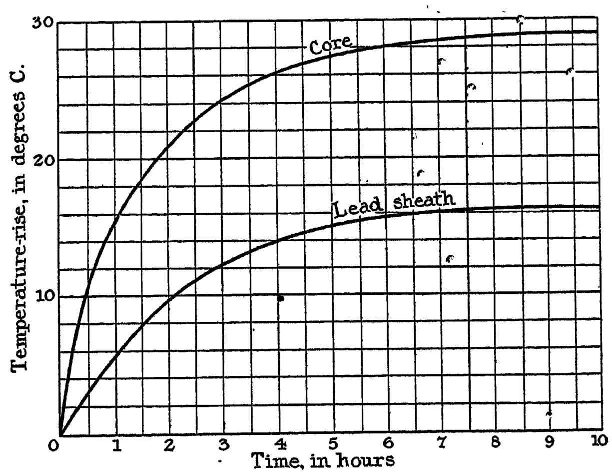

Fig. 15.—Temperature-rise in air of three-core 0·15 sq. in. 20 000-volt cable No. 22, at 200 amperes, three-phase, 25 ~.

(13) Comparison between Heating of Three-core Cables with Three-phase Current and Direct Current.

In order to determine whether there is any appreciable increase in the heating of a three-core cable when heated with three-phase alternating current over that observed with an equal direct current, a series of tests has been made on one of the cables (No. 22) as used for 20 000 volts.

The heating current was supplied by three single-phase transformers, connected as shown in Fig. 14. The current in each conductor was carefully balanced by means of a small amount of resistance in the primary circuit of each transformer.

A complete series of observations was taken, as follows :—

(*a*) With the cable lying on the floor with alternating current at a frequency of 50 cycles.

(*b*) The same conditions with alternating current at a frequency of 25 cycles.

(*c*) With the cable supported at intervals at a height of 9 in. above the floor.

The current value was in every case 200 amperes per conductor or per phase.

In order to make a resistance measurement, one conductor was opened temporarily and a direct current of approximately the same value as the alternating current was passed through the cable in series with a standard resistance. The observations in general took about 20 seconds and in no case more than 30 seconds, and the observations showed that even if the direct current were considerably different from the alternating current, this time was too short to cause any appreciable effect on the temperature of the cable.

It will be seen from Fig. 14 that the whole change of connections was made with a simple change-over switch.

Fig. 15 shows the result obtained with the cable supported 9 in. above the floor and loaded with a three-phase alternating current of 200 amperes per phase at a frequency of 25 cycles. This agrees very closely with the previous results on the same cable when tested in air with direct current in 1919, and also with the values now obtained with alternating current at frequencies of 25 cycles and 50 cycles respectively when the cable is laid on the floor. The difference of maximum temperature-rise was in fact less than 1 degree C. for all cases, and if the curves were plotted they would be indistinguishable from one another.

The results show that for cables of this size (0·15 sq. in.) there is no appreciable difference due to three-phase loading, and also dispose of a criticism levelled at the Preliminary Report that there might be a difference between the heating of a cable laid along a floor and when suspended in air.

(14) Grouped Cables laid Direct in the Ground.

It will be noted that hitherto only cables laid singly have been dealt with. There are, of course, many cases where several cables are laid near each other in the same trench, and while the widely varying practice in this respect makes it difficult to formulate a general simple rule, a method has been developed for the predetermination of the mutual effect of two or more neighbouring cables.

On Kennelly's assumption (see Teichmüller, "Die Erwärmung der Electrischen Leitungen," p. 55) a buried cable is surrounded by a series of circular eccentric isothermals the depths y of the centres of which below the surface of the ground are given by the formula :—

$$y = \left(\frac{B^2 + 1}{B^2 - 1}\right) L \quad . \quad . \quad . \quad . \quad . \quad (39)$$

and the radii f of which are given by the formula :—

$$f = \frac{2LB}{B^2 - 1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

where $$B = [M + \sqrt{(M^2 - 1)}]^{\delta} \quad . \quad . \quad . \quad (41)$$

δ being the ratio of the temperature of the isothermal to that of the surface of the cable, and M the ratio of L to r_6, the outer radius of the cable covering.

These equations enable the position and the size of the isothermal circle for any value of the temperature ratio δ to be calculated and a series of curves to be drawn as shown in Fig. 16. These show the ratio of the temperature-rise to that of the surface of the cable, plotted for any point in a horizontal plane passing through the cable axis. The shape of the curve will vary somewhat with the size of the external diameter of the cable, and therefore a series of curves is required corresponding to various values of the cable diameter. The series given in Fig. 16 applies to cables with external

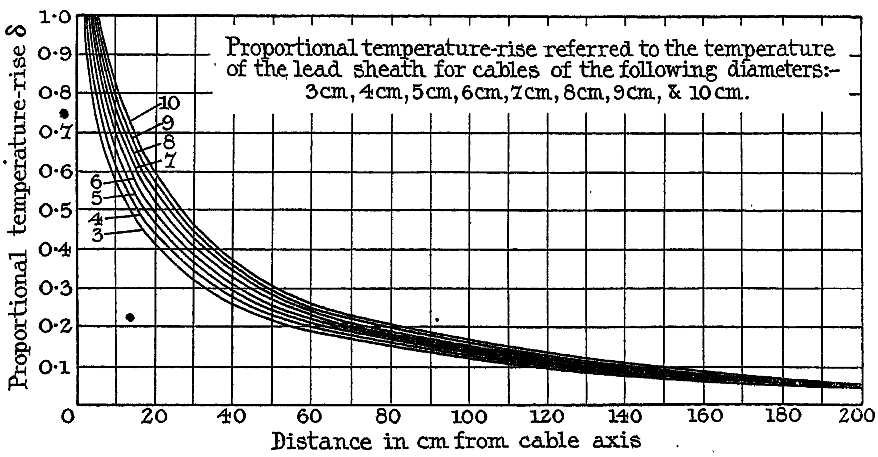

Fig. 16.—Effect due to heating of a neighbouring cable in the same horizontal plane, at a depth below the surface of the ground of 60 cm (2 ft.).

diameters ranging from 3 cm to 10 cm. The axis of the cable is 60 cm (2 ft.) below the surface of the ground in every case.

In order to determine the mutual heating effect of two or more cables, it is necessary to know the diameters of the cables under consideration and t_4, the temperature of the outer surface, when the cable is running alone at any specified current. If this is not known from direct measurement, or where, as in the case of armoured cables when buried, direct measurement would be difficult, the temperature of the outside can be obtained if the thermal constants of the cable are known, by means of the equation :—

$$t_4 = t_1 \left(\frac{S_1 + S_2}{S_1 + S_2 + G}\right) \quad . \quad . \quad . \quad . \quad (42)$$

Reference to Fig. 16 will then show the value of δ for any point in a horizontal plane passing through the axis of the cable, δ being the ratio of the temperature-rise t_x of that point due to diffusion of heat from the cable compared with the temperature t_4 of the outer surface of the cable. A second cable at this point will experience this proportional temperature-rise δ due to the first cable, in addition to that due to self-heating. The effect of other neighbouring cables can also be calculated and superposed on the first by a repetition of the process. If the permissible temperature-rise of the cable when running alone is t_1, and t_x is that due to diffusion from other cables, then the permissible current to a first approximation must be reduced in the ratio

$$\sqrt{\left(\frac{t_1 - t_x}{t_1}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

if the permissible temperature-rise is not to be exceeded.

In Tables 35 and 36 and in Fig. 17 the method in its application to the case of several cables is illustrated, and the value of the temperature-rise, as observed by actual experiment when all the cables were running together, has been added for comparison.

For any such case as the experimental one, where the size of the cables and the distance apart will vary, it is necessary to calculate for each condition. The effect of two cables laid in the same trench has, however, been considered and the results are given below

(*a*) *Two cables of the same size and type in the same horizontal plane.*—If two cables of the same size are

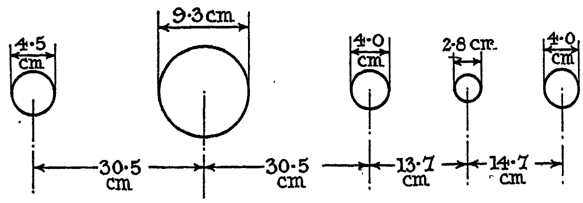

FIG. 17.—Dimensions and relative positions of grouped cables.

assumed to be 12 in. (30·5 cm) apart (between centres) the ground temperature, due to mutual influence, varies between 0·30 and 0·45 of the sheath temperature according to the size of the cable (i.e. 3 to 10 cm diameter).

TABLE 35.

*Temperature-rise of Cables laid Direct in the Ground and Loaded Singly.**

Cable ..	A	B	C	D	E
Load in amps. ..	350	150	220	220	220
Temperature-rise, deg. C. when running alone at this load	36·0 inner conductor 31·0 outer conductor 24·0 sheath	32·5 conductor 32·5 conductor 17·5 sheath	30·5 inner conductor 25·3 outer conductor 18·5 sheath	44·8 — 27·2	— 27·2 conductor 12·8 sheath
Type and size ..	0·2 sq. in concentric	0·1 sq. in. 6-core	0·1 sq. in. concentric, armoured	0·1 sq. in. concentric, lead sheathed	0·15 sq. in. 3-core

* The depth below the ground surface was 60 cm (2 ft.) in every case.

Taking $\delta = 0{\cdot}40$ as an average figure (corresponding to a cable of 7 cm diameter); and assuming the temperature-rise of the sheath to be 0·6 of that of the conductor, then if the conductor is 50 degrees C. above datum level, the temperature of the soil at a point 1 ft. distant is as follows :—

$$t_x = 0{\cdot}4 \times 0{\cdot}6 \times 50 = 12$$

t_x being the temperature at a given distance from the cable, and in the same horizontal plane. The temperature of the conductor in a second cable at that point would be raised to $50 + 12 = 62°$ C. if 50° C. were the temperature the conductor would assume with the first cable cold.

In order then to reduce the temperature-rise of this second cable to 50 degrees C., the currents must be reduced in the ratio $\sqrt{(38/50)} = 0{\cdot}87$.

TABLE 36.

*Temperature-rise of Cables laid Direct in the Ground as shown in Fig. 17 and when all Cables are Loaded.**

Diameter, cm		4·5	9·3	4	2·8	4
Proportionate temperature-rise due to the effect of cables given in next column	A	—	0·35	0·20	0·15	0·12
	B	0·45	—	0·45	0·34	0·26
	C	0·19	0·35	—	0·53	0·36
	D	0·14	0·24	0·49	—	0·48
	E	0·12	0·20	0·36	0·51	—
Temperature-rise, deg. C., due to effect of cables given in next column	A	24 sheath †	8·4	4·8	3·6	2·9
	B	7·9	32·5 conductor	7·9	5·9	4·5
	C	3·5	6·5	30·5	9·8	6·6
	D	3·8	6·5	13·3	44·8	13·1
	E	1·54	2·5	4·6	6·5	27·2
Calculated temperature-rise, i.e. sum of above, deg. C.	—	40·7	56·4	61·1	70·6	54·3
Temperature-rise by experiment, deg. C.	—	39·1 sheath	54·7	58·3	71·6	54·1

* The depth below the ground surface was 60 cm (2 ft.) in every case.
† In this cable only the sheath temperature was available when the cables were run together.

TABLE 37.

Ratios of Current Reduction due to the Heating of a Neighbouring Cable in the Same Horizontal Plane. Depth of Laying = 60 cm (2 ft.).

Cable	Size of Cable, sq. in.	Working Pressure, volts	$2r_6$ cm	t_4	δ	t_x	Ratio of Current Reduction	
				Separation, 4 *in.*				
A	0·0225	660	3·8	0·66	0·60	19·8	0·78	Mean = 0·76
B	0·0225	11 000	3·9	0·65	0·61	19·8	0·78	
C	0·25	11 000	9·0	0·57	0·78	22·4	0·74	
D	0·4	660	8·9	0·61	0·77	23·5	0·73	
				Separation, 8 *in.*				
A	0·0225	660	3·8	0·66	0·44	14·5	0·84	Mean = 0·82
B	0·0225	11 000	3·9	0·65	0·48	15·5	0·83	
C	0·25	11 000	9·0	0·57	0·56	16·0	0·82	
D	0·4	660	8·9	0·61	0·56	17·0	0·81	
				Separation, 12 *in.*				
A	0·0225	660	3·8	0·66	0·34	11·2	0·88	Mean = 0·86
B	0·0225	11 000	5·9	0·65	0·38	12·3	0·87	
C	0·25	11 000	9·0	0·57	0·44	12·6	0·86	
D	0·4	660	8·9	0·61	0·44	13·4	0·85	

(*b*) *Calculations for four different sizes of cables in the same horizontal plane.*—Consider a 0·0225 sq. in. 660-volt, three-core cable;

$$2r_6 = 3\cdot 82\,; \quad e = 0\cdot 34$$

$$\frac{S_1 + S_2}{S_1 + S_2 + G} = \frac{65 + 28\cdot 6}{142\cdot 8} = \frac{93\cdot 6}{142\cdot 8} = 0\cdot 66 \quad (44)$$

Temperature at a point 1 ft. distant

$$= 0\cdot 34 \times 0\cdot 66 \times 50 = 11\cdot 2$$

Current reduction $\sqrt{(38\cdot 8/50)} = 0\cdot 882$

And calculating other sizes of three-core cables in the same way for distances of 4 in., 8 in. and 12 in. separation respectively, the results given in Table 37 are obtained.

TABLE 38.

Ratios of Current Reduction due to the Heating of a Neighbouring Cable in the Same Vertical Plane.

L cm	At a Position 12·7 cm (5 in.) above				At a Position 12·7 cm (5 in.) below			
	45·7 (1 ft. 6 in.)		91·4 (3 ft.)		45·7 (1 ft. 6 in.)		91·4 (3 ft.)	
r_6 cm	1	4	1	4	1	4	1	4
Ratio of current reduction	0·87	0·81	0·84	0·77	0·86	0·78	0·83	0·75

TABLE 39.

Tests of Cables in Air, together with a Comparison of Calculated Currents based upon Different Values of Emissivity.

h = emissivity constant; K = thermal resistivity; I_1 = current for a temperature-rise of the conductor of 50 deg. C.

Size and Type of Cable	Working Pressure	(1) h	(2) K	(3) I_1 by Exp. $K = 550$	(4) I_1 by Cal. $h = 0·0009$	(5) I_1 by Cal. $h = 0·0008$	(6) Ratio (4)/(3)
Single-core Cables.							
	volts			amps.	amps.	amps.	
0·1 sq. in. plain lead	660	—	1 200	263	273	260	1·035
0·2 sq. in. plain lead	660	—	800	447	427	412	0·955
Concentric Cables.							
0·1 sq. in armoured	660	—	620	233	245	236	1·05
0·2 sq. in. armoured	660	—	720	355	385	369	1·08
0·2 sq. in. armoured (jute) ..	660	0·00096	870	367	375	359	1·02
0·5 sq. in. plain lead	2 200	0·00083	1 090	561	533	512	0·96
Three-core Cables.							
0·025 sq. in. plain lead (old cable)	Probably 660	—	1 050	93·5	81	77·5	0·87
0·05 sq. in. armoured	10 000	0·0011	730	142	137	134	0·96
0·1 sq. in. armoured	6 000	0·00088	420	195	201	198	1·03
0·15 sq. in. segmental conductors armoured ..	6 600	0·00086	500	251	259	251	1·03
0·15 sq. in. armoured	3 300	0·00093	608	265	253	245	0·95
0·15 sq. in. armoured	11 000	0·0010	459	267	267	261	1·00
0·15 sq. in. armoured	20 000	0·0009	535	275	273	266	0·995
0·75 sq. in. plain lead ..	660	0·00090	750	826	807	775	0·98
Six-core Cable.							
0·1 sq. in. armoured	20 000	0·00080	600	172	179	174	1·04

Values of the same order are obtained for different types and sizes of cables, and it is probable that a factor of 0·76 for a pair of cables 4 in. apart, of 0·82 for a pair of cables 8 in. apart, and of 0·86 for a pair 12 in. apart would be sufficiently accurate for all practical purposes.

(*c*) *Calculation of mutual heating effect of two cables laid in the same vertical plane.*—Let the axis of the first be laid at P_1 (Fig. 18) and that of another at P_2 vertically above it, and q cm distant. If y be the distance below the surface of the ground of the centre of the isothermal circle passing through P_2 and f its radius [see Equations (39) and (40)], then

$$y - f = L - q$$

and we have
$$\frac{B-1}{B+1} = 1 - \frac{q}{L}$$

where B has the meaning defined in Equation (41).

But M^2 is large in comparison with 1, so that very closely

$$B = \log_e 2M = \log_e (2L/r_6)$$

whence
$$\delta = \frac{\log_e(2L/q - 1)}{\log_e(2L/r_6)} \quad . \quad . \quad . \quad . \quad (45)$$

If the second cable is at P_2' below P_1

$$\delta = \frac{\log_e(2L/q + 1)}{\log_e(2L/r_6)} \quad . \quad . \quad . \quad . \quad (46)$$

The calculation of the amount by which the current-rating must be reduced is shown in Table 38 for two values of L and two values of r_6, both for the case when the axis of the second cable is 12·7 cm (5 in.) above the first, and also when it is 12·7 cm (5 in.) below.

(15) Current-rating of Cables in Air.

For the purpose of this investigation a large number of different sizes and types of cable have been examined. Tests have been made in every case with the cables laid on the wood floor of a room, and since the values so obtained are useful for purposes of determining the current-rating for cables used under these conditions, a comparison between the experimental and the theoretical

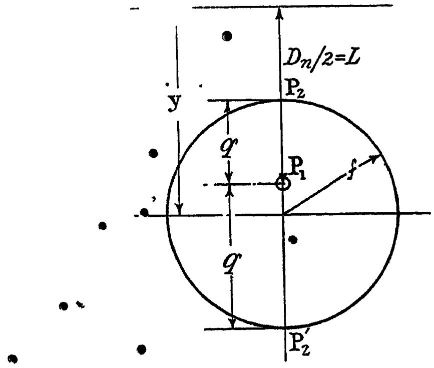

Fig. 18.—Calculation of mutual heating effect of two cables laid in the same vertical plane.

values has been made for all the cables tested. The tests carried out on a selected cable supported above the ground in free air gave, within the limits of experimental error, the same results as had been obtained with the same cable laid along a floor free from draughts (see Fig. 15). Thus the results given may be taken as applying equally to either case. The results are given in Table 39.

The general method of calculation was the same as that used for buried cables except that the term G is replaced by A, the resistance to the flow of heat from the outside surface of the cable to the surrounding air. If h is the emissivity expressed in watts per cm^2 per degree of temperature-rise of the surface above the surrounding air, then

$$A = \frac{1}{2\pi h r_6} \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

It will be seen that in Table 39, results are included for cables ranging from 0·1 sq. in. single-core to 0·5 sq. in. concentric and cables for various pressures, both plain lead-covered and armoured.

The thermal resistivity constant K has been determined for every case, and all the experimental values have been corrected for $K = 550$.

The emissivity constant h has been determined in the majority of cases and it will be seen that its values range from 0·0008 to 0·0011, depending on the exact nature of the surface of the cable.

Tests made by Mr. J. F. Watson confirm these values very closely. In this case four lengths of cable were tested: (1) with each sheath in its new bright condition, and (2) with each sheath painted a dull black. In the first series the mean value obtained was $h = 0{\cdot}00070$ and in the second $h = 0{\cdot}00107$. Details of these tests are given in Appendix VI. It is probable that the nature of the surface is more important than the colour, and from this point of view Mr. Watson's values probably represent the extremes that can be obtained. In the case of the values given in Table 39 the lead sheath was probably not so bright as that tested by Mr. Watson, and previous tests and observations in other directions indicate that when the sheath has lost its initial brightness the value is nearly the same as with a dull black surface. The same remark applies also to the armoured cables; in one case the value of 0·0011 is nearly identical with Mr. Watson's value for a dull black surface, but in others it is rather lower, depending probably on the nature of the black surface.

For the purposes of calculation, the average value of $h = 0{\cdot}0009$ has been taken, and, in order to show the extent of the difference due to emissivity, a further series of values, using $h = 0{\cdot}0008$, is also given.

(16) Correlation of Results with Cables in Air and when Laid Direct in the Ground.

The values of current required to produce a given temperature-rise with the cables in air can be connected with those required to produce the same temperature-rise when the same cables are laid direct in the ground or drawn into a duct.

It can be shown that the relation between the two values of current required to produce a given temperature-rise under the two conditions is

$$\frac{I_2}{I_1} = \sqrt{\left(\frac{S + A}{S + G}\right)} \quad . \quad . \quad . \quad . \quad . \quad (48)$$

where A = thermal resistance per cm of cable to the flow of heat from the surface of the cable to the air.

I_1 = current for a given temperature-rise when the cable is in air.

I_2 = current for the same temperature-rise when the cable is laid direct in the ground or drawn into a duct.

This formula enables the heating of a cable laid direct in the ground or drawn into a duct to be deduced from the value obtained when tested in air, and the calculated results are in fair agreement with those derived from experiment. As stated above, however, the emissivity constant h is not easy to determine accurately, and it is probable that a more convenient method would be to make a determination of the total heating of the conductors and the temperature gradient between the conductor or conductors and the sheath by means of observation of the temperature of the lead covering. This also would enable the behaviour of the same cable when buried to be deduced.

The factors for cables drawn into ducts vary, as will be seen from Table 41, from 0·935 to 0·98, a mean value of 0·95 nearly representing all sizes of cables. In the case of armoured cables laid direct in the ground, as would be expected, the values change with varying thickness of dielectric. Actual experiments on cables gave the approximate values shown in Table 40 for the same rise in temperature for each cable in air and when buried direct in the ground.

TABLE 40.

Current Ratios for Cables when in Air and laid Direct in the Ground at a Depth of 2 ft., $g = 90$.

Type of Cable	Working Pressure, volts	$\frac{I_2}{I_1}$
0·1 sq. in. concentric ..	660	1·22
0·2 sq. in. concentric ..	660	1·21
0·15 sq. in. three-core ..	3 300	1·13
0·15 sq. in. three-core ..	11 000	1·09
0·15 sq. in. three-core ..	20 000	1·04

It should be understood that the correlation refers only to the case where the cable in air is laid out either in free air or along a wood floor free from draughts.

(17) CURRENT-RATING OF CABLES DRAWN INTO DUCTS.

In the Preliminary Report it was shown (Table 6) that the current required to produce a given temperature-rise when a cable was drawn into a duct was nearly the same as when the same cable was tested in air, and that this applied whatever the relative sizes of cable and duct. A further check has been made by drawing into one of the holes in the duct shown in Fig. 20 the 11 000-volt cable which had previously been tested both when laid in air and direct in the ground. Fig. 19 shows the temperature-rise curves for the three conditions. The ratio of the currents I_2/I_1 to produce a given temperature-rise for this cable when in a duct is 0·93.

The full list of the cables for which this ratio was determined, including those given in the Preliminary Report, is given in Table 41.

The values given in Table 41 suggest that the main resistance to the flow of heat is in the layer of air immediately surrounding the cable, and that the relative dimensions of cable and duct and the material of the duct make little difference to the value of the current required to produce a given temperature-rise. The difference in the value of the ratio I_2/I_1 between the armoured cable and the others, which were plain lead-sheathed, is probably due to the fact that the emissivity constant of the armoured surface was higher than that of the plain lead, in consequence of which the air condition value for this cable would be higher. The fact that the cable was larger and filled the hole in the duct more completely would appear to have little influence on the results.

Also it seems clear that variation in the resistivity of the surrounding soil will have little effect on the heating of a cable in a duct.

It was decided that current-loading tables should be calculated for one cable drawn into a duct or pipe, the ratio I_2/I_1 being taken as 0·95, corresponding to a permissible temperature-rise of 35 deg. C.

TABLE 41.

Comparison of Current Ratings for Cables in Air and drawn into Ducts.

Size and Type of Cable	Working Pressure	External Diameter	I_2	I_1	$\frac{I_2}{I_1}$
	volts	in.	amps.	amps.	
0·1 sq. in. concentric	660	$1\frac{1}{16}$	130	133	0·98
0·2 sq. in. concentric	660	$1\frac{7}{16}$	243	252	0·96
0·5 sq. in. concentric	660	$2\frac{1}{8}$	370	378	0·98
0·1 sq. in. three-core	660	$1\frac{1}{4}$	157	162	0·97
0·1 sq. in. three-core	Probably 11 000	$2\frac{1}{4}$	162	170	0·95
0·15 sq. in. three-core armoured ..	11 000	$2\frac{7}{8}$	220	235	0·935

I_1 = current required to produce a given temperature-rise when the cable is in air.
I_2 = current required to produce the same temperature-rise when the cable is drawn into a duct.
Diameter of hole in duct = $3\frac{1}{2}$ in.

(18) GROUPED CABLES DRAWN INTO DUCTS.

Tests were made to determine the effect of running all the cables in the six-way duct at the same time, and the temperature-rise on two of the cables was measured. The actual arrangement is shown in Fig. 20. The two cables measured were located in holes Nos. 1 and 6. Each cable was a 0·2 sq. in. concentric cable carrying 200 amperes, the power for the length of 100 ft. being approximately 360 watts for each cable. Of the other four cables in the duct, Nos. 2, 3 and 4 were dissipating 165 watts each, and No. 5, 600 watts. Thus the total power in the whole duct when all the cables were running was 1 800 watts per 100 ft. The curves in Fig. 21 show the actual heating of the 0·2 sq. in. cables

both when running singly and in a group. It will be noted that the time required to attain to the maximum temperature is somewhat longer when the cables are grouped, and that the temperature-rise is appreciably higher.

(19) Time required for Cables to attain Maximum Temperature.

The time required for a cable to attain its maximum temperature varies somewhat with the type of cable and the method of laying. In the Preliminary Report

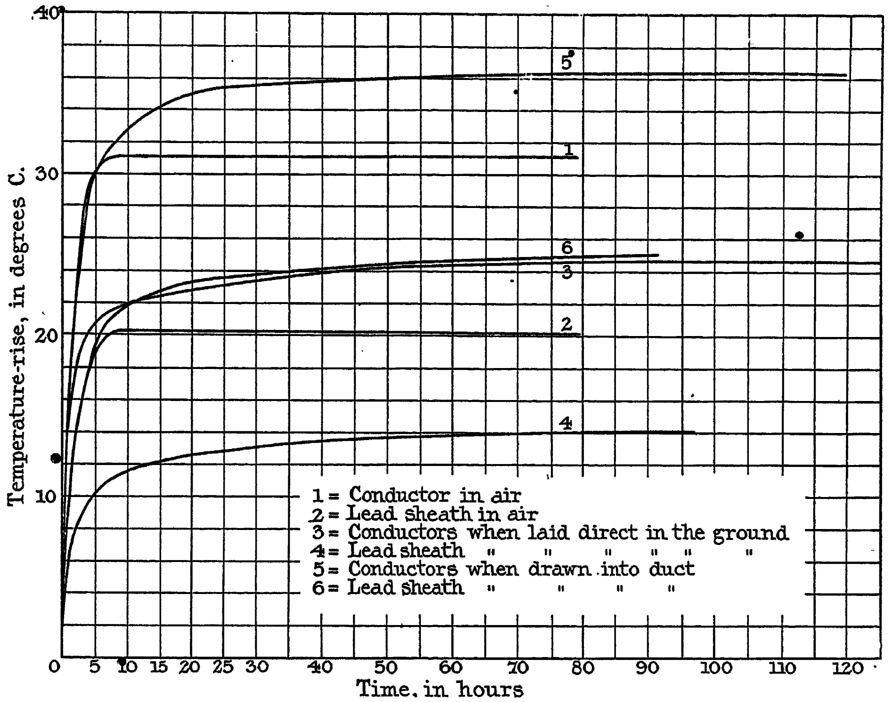

Fig. 19.—Temperature-rise of three-core 0·15 sq. in. 11 000-volt cable laid under different conditions; current = 220 amps.

Values of current calculated from the heating curves in Fig. 21 show that, as a result of grouping, the current must be reduced to 89 per cent of its value when only one cable is carrying current; for a similar cable

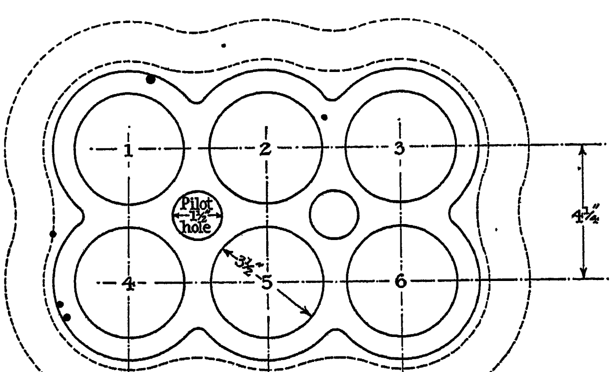

Fig. 20.—Plan of stoneware duct.

drawn into the lower hole in the duct the value was 90 per cent. Comparison of the last two values shows that there is no appreciable difference between the upper and lower holes of the duct.

it was shown that cables drawn into ducts attained 98 per cent of their maximum temperature in 30 hours, laid solid 92·5 per cent, and laid direct in the ground 91·4 per cent. These values have been fully checked as a result of points raised in the discussion on the Preliminary Report. Taking first the effect of different methods of laying, Fig. 19 shows the curves for an 11 000-volt cable tested at the same current values in air, laid direct in the ground, and drawn into a duct.

It will be seen that in air the cable has attained its maximum temperature in 10 hours, whilst when drawn into a duct it has reached 96·5 per cent of its maximum in 20 hours, and when laid direct in the ground 92 per cent in 20 hours, the maximum temperature in the last case being attained after 5 days. It is, however, most difficult to state the time for maximum temperature accurately, since the rise during the latter portion is very slight and is masked by such factors as fluctuation of ground temperature, small changes of current and limits of error of observation.

Fig. 22 shows the heating curves of cables for various pressures. It will be seen that generally the time required is about 5 days, although for the higher pressure cables it is somewhat shorter and for the cables as used for 20 000 volts probably nearer two to three days. The observations have been extended to cover a period of 15 days, and during the last 9 days of each

run there was certainly not a rise of 1 degree C. for the whole of the period, which value is nearly the limit of total error of observation when all the variable factors are taken into account.

ing loading when regular in character by means of calculations based on the thermal time-constant of the cable involved. This has been fully dealt with in a paper by Messrs. S. W. Melsom and H. C. Booth.*

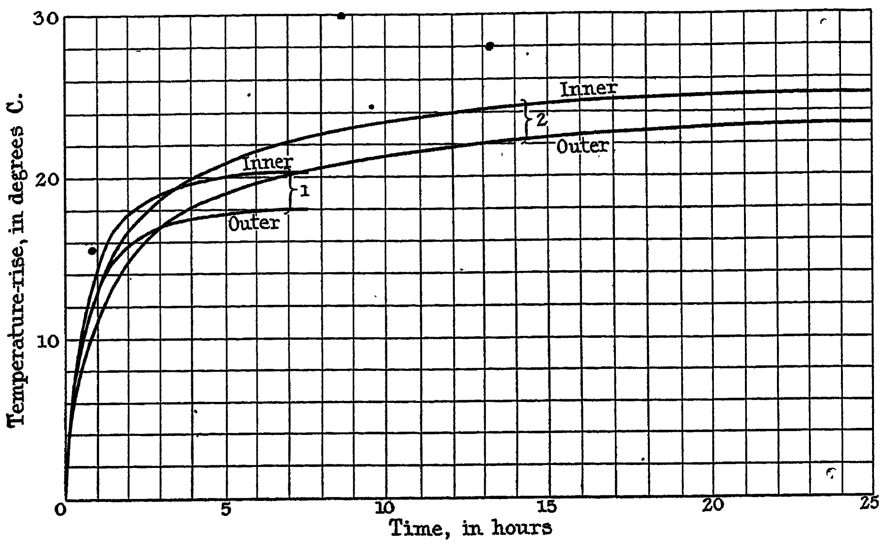

FIG. 21.—Temperature-rise of concentric 0·2 sq. in. 660-volt cable in stoneware duct.

Curves marked 1: one cable only carrying current.
Curves marked 2: six cables carrying current.

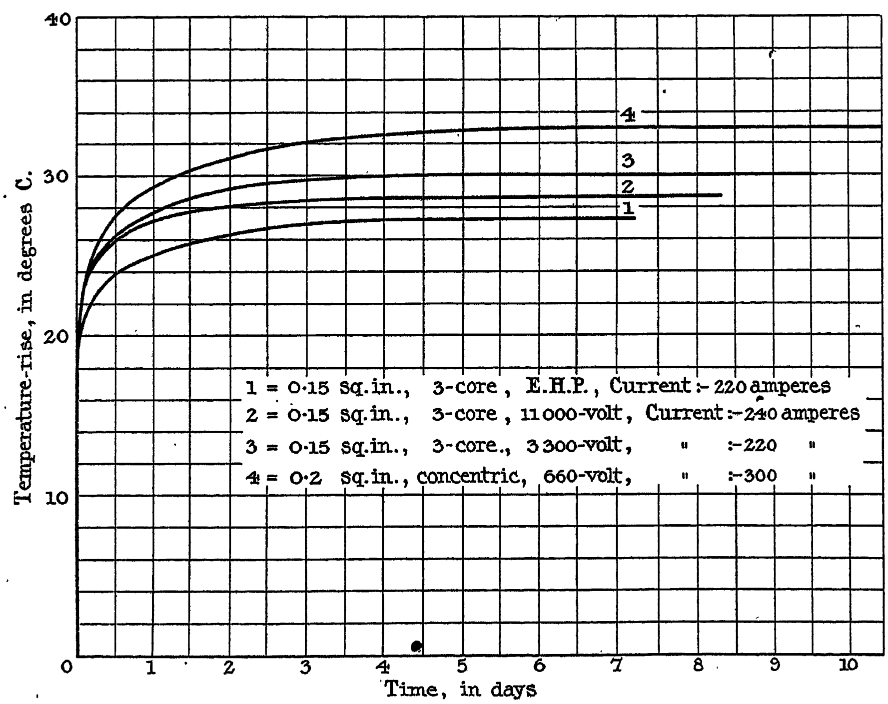

FIG. 22.—Temperature-rise of armoured cables, with various thicknesses of dielectric, laid direct in the ground.

(20) CURRENT-RATING OF CABLES FOR CYCLICAL INTERMITTENT LOADING.

For cables running in air it is possible to estimate with sufficient accuracy for practical requirements the effect on the current-rating of intermittent or fluctuating loading when regular in character by means of calculations based on the thermal time-constant of the cable involved.

For cables laid underground it is not possible to find a thermal time-constant and the problem becomes more complicated and does not lend itself so readily to mathematical treatment. The heating and cooling

* *Journal I.E.E.*, 1923, vol. 61, p. 363.

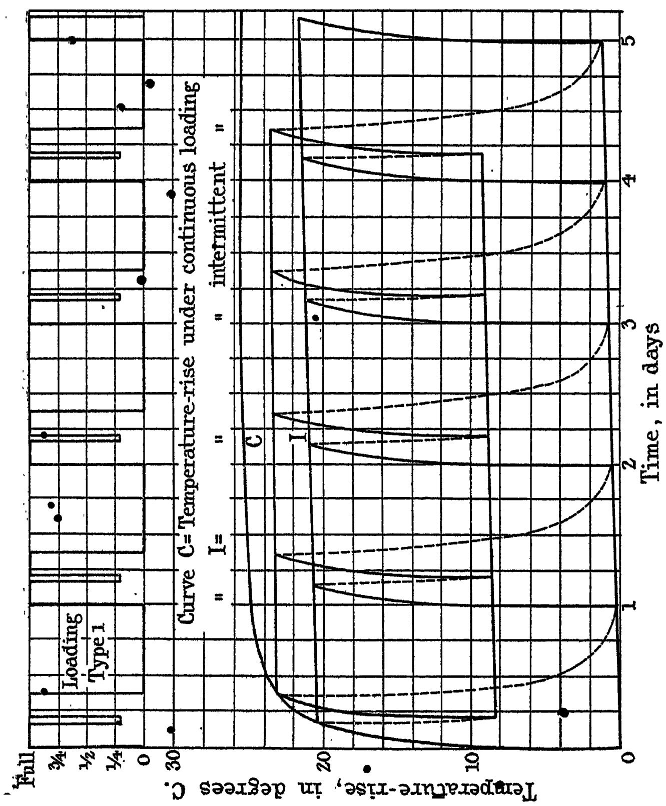

FIG. 23.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground; current = 200 amps.

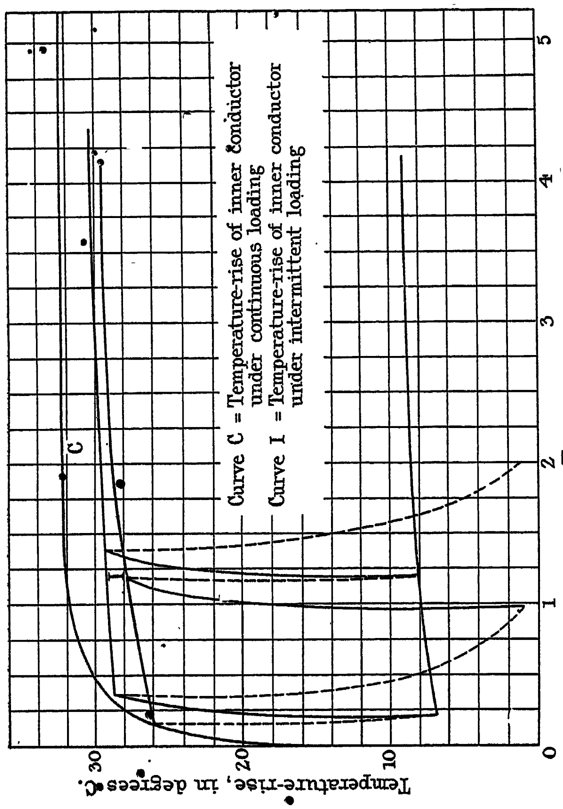

FIG. 24.—Concentric 0·2 sq. in. 660-volt cable laid solid in bitumen; current = 300 amps.; type of loading 1 (Fig. 23).

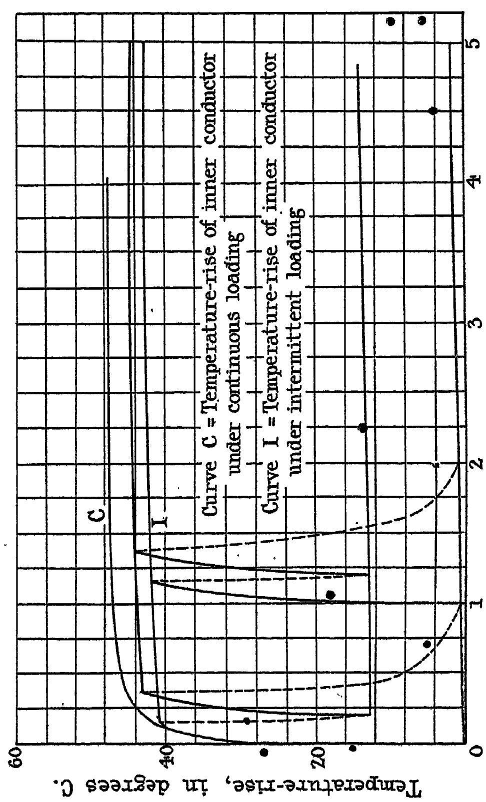

FIG. 25.—Concentric 0·25 sq. in. 660-volt cable in stoneware duct; current = 300 amps.; type of loading 1 (Fig. 23).

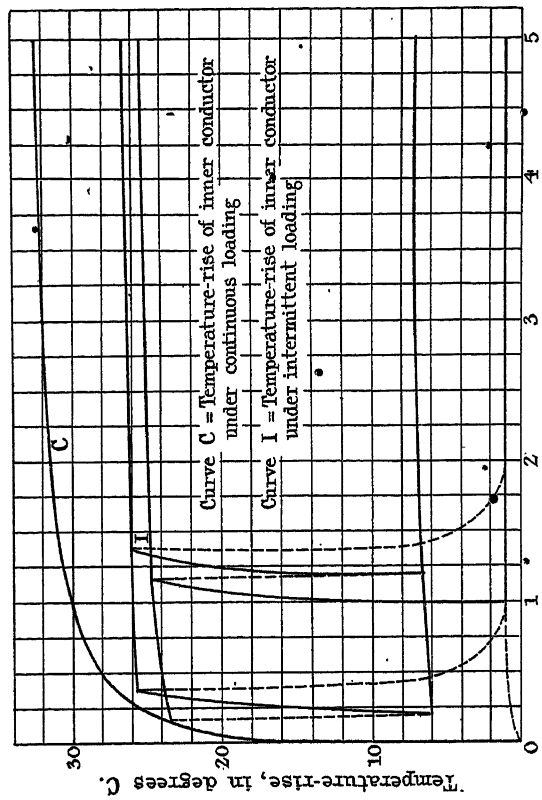

FIG. 26.—Concentric 0·2 sq. in. 660-volt armoured cable laid direct in ground; current = 300 amps.; type of loading 1 (Fig. 23).

curves of cables running in air are found to follow a simple exponential formula fairly closely, since the necessary assumption that the whole of the cable and covering is heated approximately simultaneously by the passage of the current is sufficiently closely justified for the limits of accuracy required. But such a formula does not apply when the same cable is buried, owing to the essentially different conditions that then obtain, for when buried the cable is surrounded by a medium of practically infinite heat capacity through which the heat is slowly diffused.

Cables laid direct in the ground.—In view of the difficulty of predetermining values for intermittent loading by means of a thermal time-constant, several tests have been made to determine the additional current, if any, that could be carried by a cable when the loading was more in accordance with the normal load curves of feeder cables.

TABLE 42.

Current = 200 *Amperes; Temperature-rise for Continuous Rating* = 25·5 *degrees C. Type of Loading* (1).

Time in Intermittent-loading Test	Temperature-rise	Ratio of Currents for the Same Temperature-rise
	deg. C.	amps.
At end of 1st hour ..	13·5	275/200
At end of 2nd hour ..	17·0	245/200
At end of 3rd hour ..	19·0	230/200
At end of 4th hour ..	20·0	224/200
1 day (9-hour loading) ..	23·2	210/200
2 days	23·4	209/200
3 days	23·5	208/200
4 days	23·6	208/200

Four types of loading were dealt with :—

(1) 4 hours at full load.
 1 hour at $\frac{1}{3}$ load.
 4 hours at full load.
 Off for the remainder of the day (corresponding to the loading of a power cable working for a normal 8-hour day).

(2) 2 hours at full load.
 1 hour at $\frac{1}{2}$ load.
 2 hours at full load.
 Remainder of day at $\frac{1}{2}$ load (typical of a combined lighting and power load).

(3) The cables carrying $\frac{1}{2}$ load continuously with peaks to full load of 1, 2, 4 and 8 hours' duration respectively. (To ascertain the extent, if any, by which a cable could be overloaded for short periods.)

(4) The same as (3) but carrying 75 per cent of its normal load continuously.

In all cases the temperature-rise under the intermittent loading is compared with that attained when the maximum load is maintained continuously. For the purpose of this comparison it was necessary to correct the values of the varying thermal resistivity of the soil, and it was more convenient to correct the figures for continuous running than those for the intermittent loads. Thus, although the two sets of values for a particular cable are strictly comparable, they cannot necessarily be compared one cable with another.

(*a*) Type of loading (1) :

A 0·15 sq. in. three-core cable as used for 20 000 volts, armoured, laid direct in the ground. Maximum current = 200 amperes.

The temperature-rise of this cable during the first 4 hours and at the end of the first day, together with the current that could be carried if the cable were used only for periods of from 1 to 4 hours and for one day upwards, are given in Table 42. The complete heating curve is shown in Fig. 23, curve C representing the continuous running condition, and I the intermittent, and the final temperature is given in Table 43.

Three other cables, 0·2 sq. in. 660-volt concentric, laid under different conditions were tested under the same conditions of loading. The results are summarized in Table 43, and are shown in Figs. 24, 25 and 26.

In the curves the actual rate of heating is plotted for the first three days, and after that the upper, intermediate and lower points are shown, joined by a line. The upper curve in each case represents the rise of temperature when the cable is loaded continuously.

Referring to Table 42, at the end of the first hour the temperature-rise was 13·5 degrees C., and if this cable were run for 1-hour periods only with a long interval between the loads, the current for the same temperature-rise as under continuous loading condition could be increased in the ratio of 275/200. After one day with this type of loading the ratio of currents was 210/200, and at the end of five days 208/200. Thus the permissible increase for a normal week's working under these conditions would be only 4 per cent.

Table 43 shows, as would be expected, that the greatest possible overload applies to the 660-volt cable buried direct in the ground. Here the increase is about 10 per cent, but for the other cables it is only of the order of 3 per cent.

(*b*) Type of loading (2) :

For this type of loading the results of the tests on the 660-volt cables are shown in Figs. 27, 28 and 29 and on the cable as used for 20 000 volts in Fig. 30. The results of the tests on all the cables are given in Table 44.

(*c*) Type of loading (3) :

This test has been made only with the cable as used for 20 000 volts, the temperature-rise being shown in Table 45 and in Fig. 31.

(*d*) Type of loading (4) :

The results of tests on a cable as used for 20 000 volts are given in Table 46, and are shown in Fig. 32.

In general, the possible increases of current are not large, although it should be noted that in the case of intermittent loading the maximum temperature is maintained for a short time only, and it is possible that larger currents could be carried for short periods.

The results obtained so far do not justify a recommendation for an increase in the permissible current

TABLE 43.

Type of Loading (1).

Description of Cable and Laying	Temperature-rise after 5½ Days' Running		Ratio of Currents for the Same Temperature-rise
	Continuous	Intermittent	
	deg. C.	deg. C.	amps.
0·2 sq. in concentric, 660-volt, armoured and laid direct in ground	32·5	26·6	330/300
0·2 sq. in. concentric, 660-volt, lead-covered and drawn into a duct	47·2	44·4	309/300
0·2 sq. in. concentric, 660-volt, lead-covered and laid in bitumen	32·4	30·4	309/300
0·15 sq. in. three-core as used for 20 000 volts, armoured, laid direct in ground	25·5	23·7	207/200

TABLE 44.

Type of Loading (2).

Description of Cable and Laying	Temperature-rise after 5½ Days' Running		Ratio of Currents for the Same Temperature-rise
	Continuous	Intermittent	
	deg. C.	deg. C.	amps.
0·2 sq. in. concentric, 660-volt, armoured and laid direct in ground	32·5	27·5	327/300
0·2 sq. in. concentric, 660-volt, lead-covered and drawn into a duct	47·2	44·8	308/300
0·2 sq. in. concentric, 660-volt, lead-covered and laid in bitumen	32·4	30·1	310/300
0·15 sq. in. three-core as used for 20 000 volts, armoured and laid direct in ground	27·6	22·8	242/220

TABLE 45.

Current = 220 *Amperes; Temperature-rise for Continuous Running* = 27·4 *deg. C. Type of Loading* (3).

Hours	Temperature-rise	Ratio of Currents
	deg. C.	amps.
1	18·9	265/220
2	21·7	248/220
3	23·1	240/220
4	24·3	234/220
5	24·7	231/220
6	24·8	231/220
7	24·9	230/220
8	25·0	230/220

TABLE 46.

Current = 220 *Amperes; Temperature-rise for Continuous Running* = 27·4 *deg. C. Type of Loading* (4).

Hours	Temperature-rise	Ratio of Currents
	deg. C.	amps.
1	22·8	240/220
2	24·5	232/220
3	25·4	228/220
4	25·8	226/220
5	26·2	225/220
6	26·6	223/220
7	26·9	222/220
8	27·0	221/220

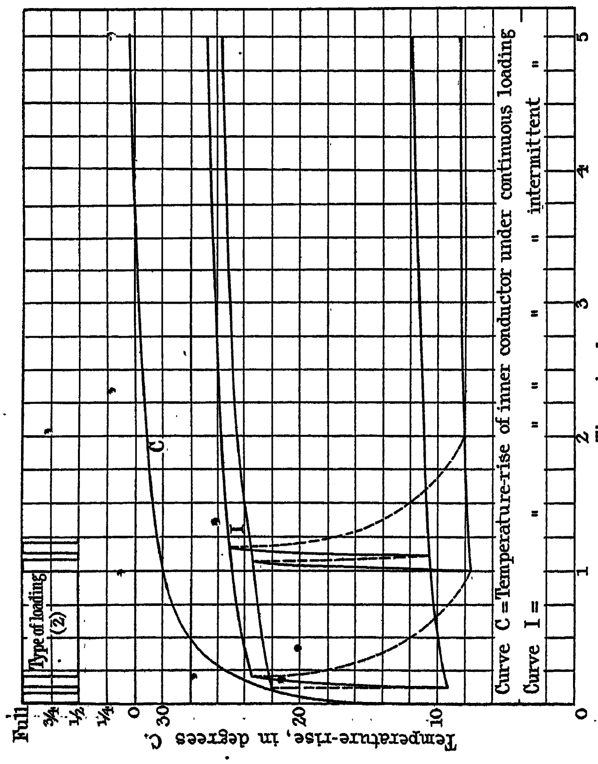

FIG. 27.—Concentric 0·2 sq. in. 660-volt armoured cable laid direct in ground; current = 300 amps.

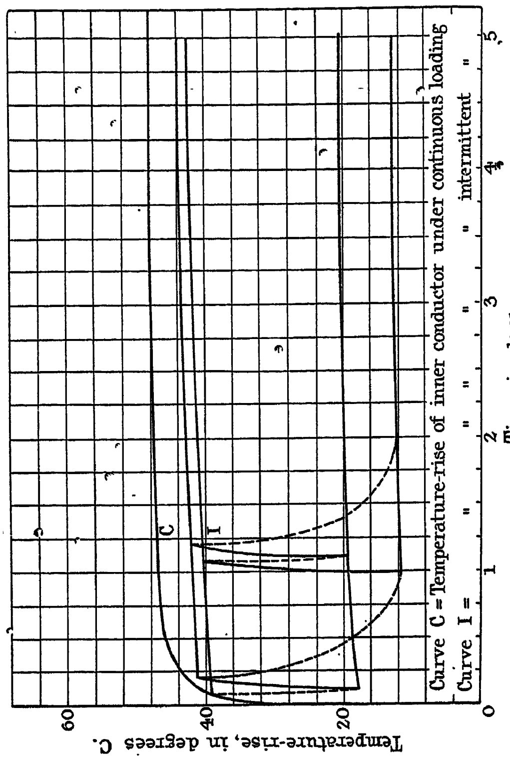

FIG. 28.—Concentric 0·2 sq. in. 660-volt cable in stoneware duct; current = 300 amps.; type of loading 2 (Fig. 27).

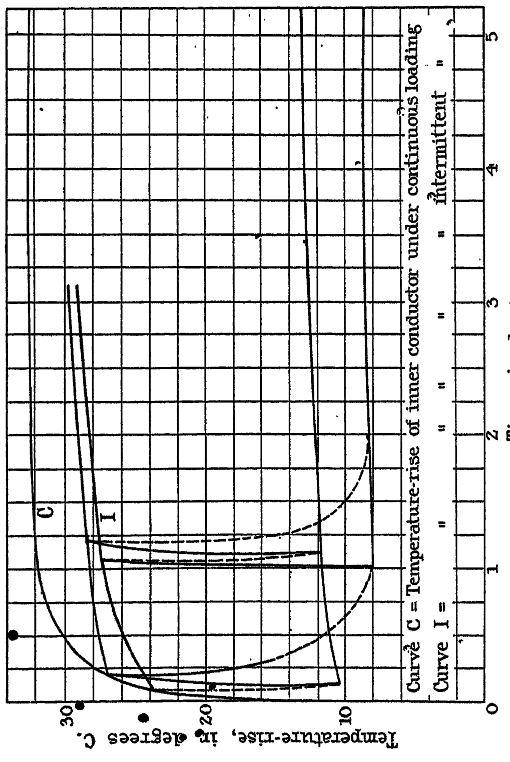

FIG. 29.—Concentric 0·2 sq. in. 660-volt armoured cable laid solid in bitumen; current = 300 amps.; type of loading 2 (Fig. 27).

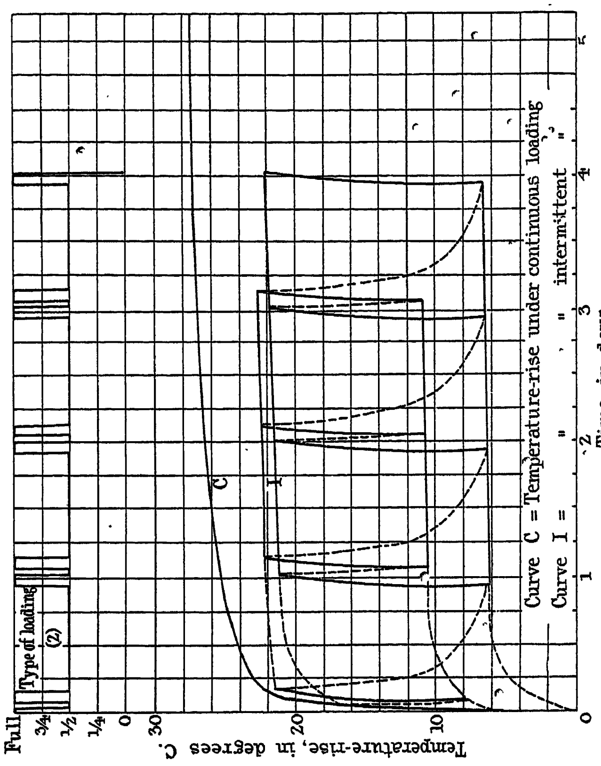

FIG. 30.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground; current = 220 amps.

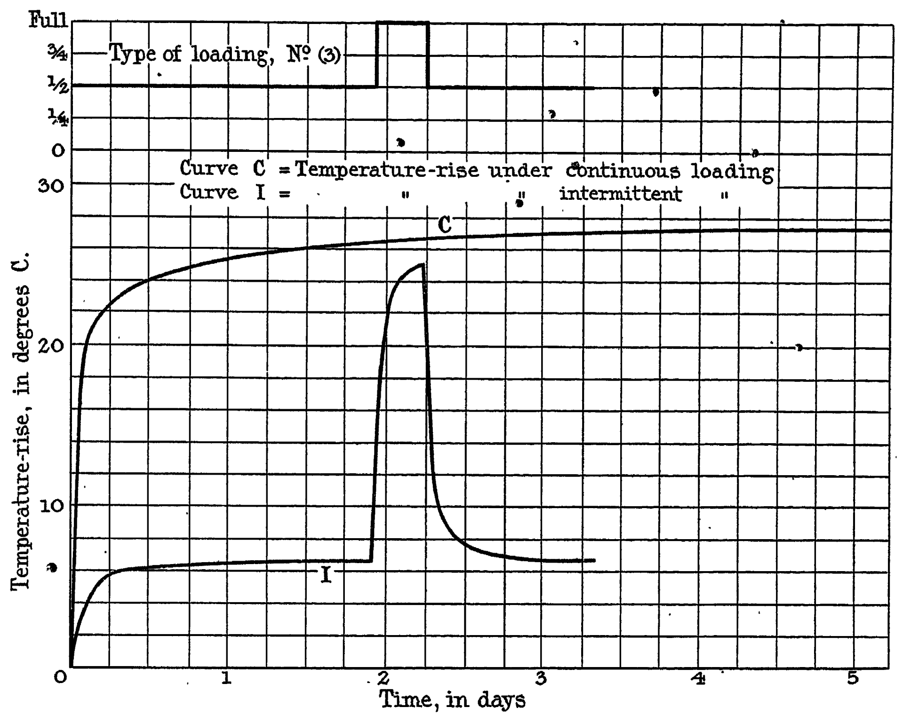

FIG. 31.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground; current = 220 amps.

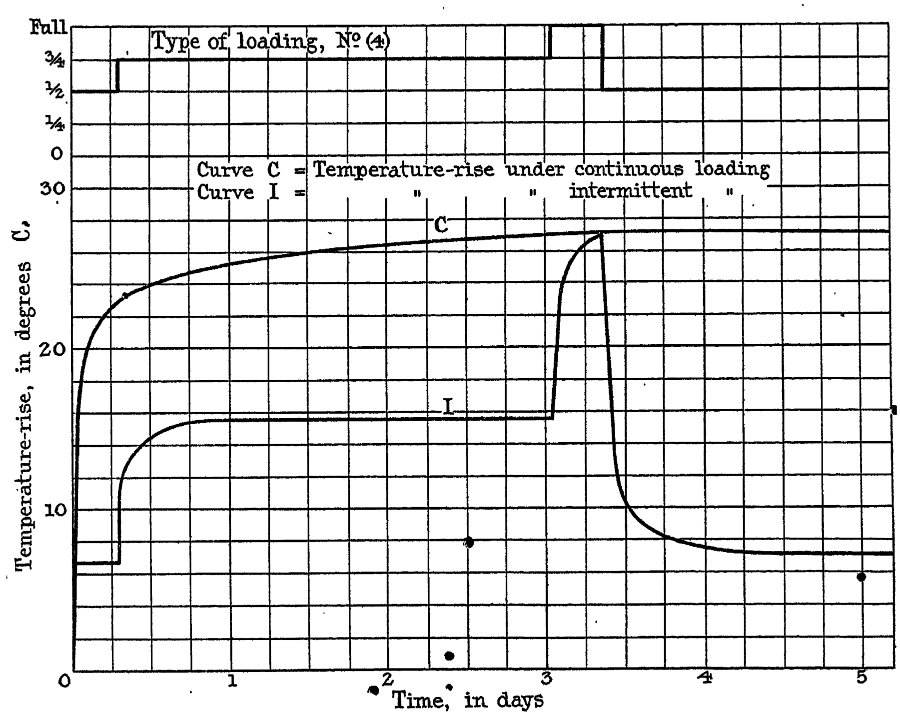

FIG. 32.—Three-core 0·15 sq. in. 20 000-volt armoured cable laid direct in ground; current = 220 amps.

loading for the conditions that have been investigated. Further tests are being made with a type of loading more nearly approximating to that on a traction circuit.

(21) Current-rating of Cables for Emergency Loading.

A feeder operating at less than full load continuously will carry more than the normal permissible maximum current for a short time without exceeding the specified temperature-rise. In the case of large cables the increment is very considerable if the cable has been previously operating on three-quarters of the normal maximum load or less. A time/temperature-rise curve for the cable laid in the specified manner, between the limits 0 and 50 degrees C. ultimate, called the "characteristic," is all that is required to obtain the permissible emergency load after any known previous steady condition.

Taking the simplest case, as when the cable has not been carrying any load previously, the permissible emergency current is deduced by setting off the emergency time on the "characteristic" starting from zero; then the square root of the ratio that 50 bears to the temperature-rise reached in the short time selected gives the multiplier for that time to apply to the continuous permissible current. Thus, if on the "characteristic" the temperature-rise after one hour is 25 degrees C., the multiplying factor is 1·414, which means that that particular cable laid in that manner will carry, starting from cold, for one hour 41·4 per cent more current than the maximum continuous rating, without exceeding the maximum permissible temperature-rise.

Table 47.

Comparison between the Values of Actual Temperature-rise and those deduced from the Simple Exponential Law.

Percentage of Maximum Continuous Current	Final Temperature-rise by Formula (38)	Approximate Rise by Square Law
per cent	deg. C.	deg. C.
50	10·85	12·5
75	25·8	28·1
100	50·0	50·0

If the cable has previously been carrying load continuously, the relative temperature-rise for this load is calculable from Formula (38), and this rise is taken as the starting point on the "characteristic." The emergency time is then set off from this point, and the total temperature-rise from zero read off and treated as before, thus giving the multiplying factor for that time under those conditions.

Owing to the cumulative heating effect of the temperature coefficient of copper, the final temperature-rise due to continuous loading is of course not strictly proportional to the square of the current: the comparative values for a maximum temperature-rise of 50 degrees C. are given in Table 47.

The values given in Table 47 of course assume that the thermal resistance outwards from the conductor is constant throughout.

Tests have been made at the National Physical Laboratory on a 0·15 sq. in., three-core, lead-covered and armoured cable, and at Newcastle-upon-Tyne on a 0·35 sq. in. similar cable, in each case laid direct in the ground at a depth of 2 feet, on type of loading (3) referred to in the previous section.

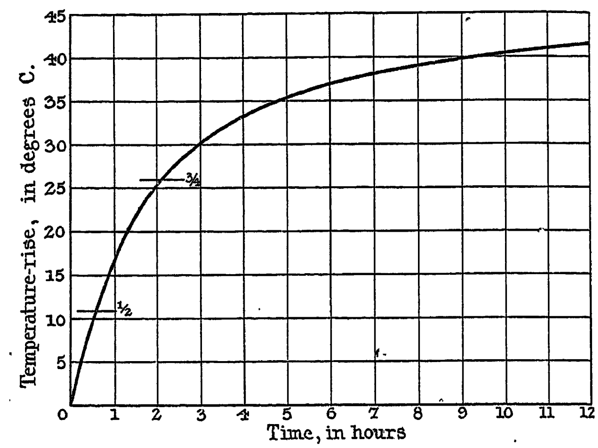

Fig. 33.—Characteristic curve of three-core 0·35 sq. in. 20 000-volt lead-covered and armoured cable laid direct in the ground; ultimate temperature-rise = 50 degrees C.

The Newcastle tests took the following form:—

(*a*) A full-load "characteristic" to give a final temperature-rise of 50 degrees C. in 72 hours. This curve is shown in Fig. 33, and on it are marked the corresponding points 10·85 degrees C. for ½ normal and 26·0 degrees C. for ¾ normal load respectively. From these points 1, 2, 3 and 4 hours were set off and the corresponding total temperature-rises read. These give the multiplying factors to apply to the normal maximum continuous current.

Table 48.

Multiplying Factors to obtain Emergency Current from Maximum Permissible Continuous Rating: Three-core, Lead-covered and Armoured Cable as used for 20 000 Volts, laid Direct in the Ground.

Size of Cable ..	0·15 sq. in.		0·35 sq. in.			
Previous Proportion of Full Load	Half	Three-quarter	None	Half — Method (*a*)	Half — Method (*b*)	Three-quarter
Emergency Time, hours						
1	1·205	1·097	1·74	1·48	1·46	1·28
2	1·125	1·057	1·40	1·32	1·316	1·225
3	1·09	1·04	1·285	1·254	1·252	1·187
4	1·06	1·03	1·22	1·20	1·22	1·162

(b) After running at a known load till steady, it was doubled and the total rises read at the end of each hour. These give multipliers obtained entirely by test which correspond closely to those calculated for the ½-load condition in (a).

(c) After running at ½ load till steady, the 1-hour emergency overload (namely, 1·48 times the maximum continuous rating) was applied for exactly one hour, and the total temperature-rise checked out at exactly 50 degrees C.

The values given in Table 48 show that two cables similar in every way except size have very widely different emergency factors. The ratio of capacity for heat (which depends on the area of the complete cable) to radiating surface (which depends on circumference) of course increases largely as the diameter increases, so that the larger cable has naturally a much greater emergency factor.

The thermal time-constant also depends on the specific heat of the materials, the dielectric having a specific heat at least three times that of copper, so that high-voltage cables exhibit a somewhat different characteristic from low-voltage ones. Owing to the many variables involved, a "characteristic" should be taken for each case on which accurate information is sought.

(22) Work Still Outstanding.

Whilst, as will be seen from the report, large sections of the programme have been completed, there are necessarily certain portions of the investigation which are not yet finished. These are :—

(a) Cables for pressures above 11 000 volts:

A large amount of work has already been done, but in view of the fact that the determination of the dielectric losses is not yet completed, it was decided to defer the issue of current-loading tables for such cables until all the information is available.

(b) Safe maximum temperature:

It has not been possible to make much progress with this section, and therefore it was decided to adopt a maximum temperature for cables for pressures of 11 000 volts and under, which was known to be safe.

(c) Three-core cables with segmental conductors:

It is appreciated that these cables are largely used. The determination of the rating depends, however, on the size of the cable and the shape of the segmental conductors. There are no standard dimensions for such cables, and until these are forthcoming it is only possible to give results based on assumed dimensions.

(d) Grouping of cables in ducts:

Further work is required to ascertain the effect of running a large number of cables in a multi-way duct.

(e) Cables laid on the solid system:

A number of determinations have been made of the thermal resistivity of the compounds used for filling the troughing. The values obtained vary largely, and further investigation is required before current-loading tables can be issued.

(23) Acknowledgment.

The Research Association desires to express its appreciation of the excellent work of the investigators, Messrs. S. W. Melsom and E. Fawssett, and their assistants, Messrs. H. C. Booth, S. D. Anderson and H. Parry, and of the invaluable assistance of Messrs. J. R. Beard, C. Vernier, J. F. Watson and B. Welbourn, who have collaborated in this research.

The Association is indebted to the Newcastle-upon-Tyne Electric Supply Co., Ltd., for continued co-operation and provision of facilities for the tests carried out in the North-Eastern district; also to those members of the C.M.A. who have supplied further cables for test.

ADDENDUM TO THE REPORT.

(*Received* 8*th May*, 1923.)

It is now understood that the values quoted on page 541 as having been suggested by various American investigators for the maximum permissible temperature for paper-insulated cables do not necessarily refer to continuous loading conditions. Mr. Torchio has pointed out that the figures he suggested refer to a recommendation that the old double, or overload, rating should be again established in the rating of electrical machinery and cables, and for this overload condition the limit of 105° C. to 110° C. was suggested with the proviso that the overload should not exceed 2 hours in duration, with a total duration of less than 10 per cent of the total hours in the year. For continuous rating a temperature of from 85° C. to 90° C. was considered to be the maximum safe limit.

[The Appendixes to the Report will be found on pages 562–579.]

APPENDIX I.

TABLE 49.

Particulars of the Paper-insulated, Lead-covered Cables employed in the Investigation.

(1)	(2)		(3)	(4)	(5)	(6)	(7)		(8)
Cable No.	Sectional Area		Type of Cable	Working Pressure	Approx. Length	Armoured	Tested		Dates of Manufacture (approx.)
	Nominal	Actual					In Air	In Ground	
			Single-core Cables.						
	sq. in.	sq. in.		volts	feet				
1	0·1	0·094	Single-core	660	110	No	Yes	Yes	1916
2	0·2	0·196	Single-core	660	110	No	Yes	Yes	1916
			Concentric Cables.						
3	0·1	0·108	Concentric	660	110	Yes	Yes	Yes	1916
4	0·1	0·099	Concentric	660	110	No	Yes	Yes	1916
5	0·1	0·100	Concentric	660	230	No	Yes	Yes	Old *
6	0·2	0·192	Concentric	660	110	No	Yes	Yes	1916
7	0·2	0·196	Concentric	660	120	No	Yes	Yes	1918
8	0·2	0·197	Concentric (jute insulated)	660	110	(Jute covered)	Yes	Yes	Old *
9	0·2	0·205	Concentric	660	110	Yes	Yes	Yes	1916
10	0·5	0·480	Concentric	660	110	No	Yes	Yes	1916
			Three-core Cables.						
11	0·025	0·029	3-Core	660	30	No	Yes	No	Old
12	0·05	0·048	3-Core (segmental conductors)	11 000	51	Yes	Yes	No	1916
13	0·1	0·105	3-Core	6 600	99	No	Yes	Yes	Old *
14	0·1	0·100	3-Core (segmental conductors)	660	114	No	Yes	Yes	Old *
15	0·1	0·101	3-Core (segmental conductors)	6 600	30	Yes	Yes	No	Old *
16	0·15	0·150	3-Core (segmental conductors)	6 600	30	Yes	Yes	No	1916
17	0·15	0·145	3-Core	20 000	50	Yes	Yes	No	1919
18	0·15	0·145	3-Core	20 000	50	Yes	Yes	No	1919
19	0·15	0·147	3-Core	20 000	50	Yes	Yes	No	1919
20	0·15	0·145	3-Core	20 000	50	Yes	Yes	No	1919
21	0·15	0·144	3-Core	20 000	50	Yes	Yes	No	1919
22	0·15	0·145	3-Core	20 000	50	Yes	Yes	No	1919
23	0·2	0·120	Nos. 23 to 26 are 3-phase split-conductor cables, each 0·2 sq. in. sect. area per phase: 6-Core	20 000	66	Yes	Yes	No	1919
24	0·2	0·116	6-Core	20 000	84	Yes	Yes	No	1919
25	0·2	0·208	Twin split	3 300	30	Yes	Yes	No	1919
26	0·2	0·200	Oval concentric	20 000	72	Yes	Yes	No	1919
27	0·25	0·250	3-Core	11 000	30	Yes	Yes	No	1916
28	0·15	0·148	3-Core	3 300	116	Yes	Yes	Yes	1921
29	0·15	0·148	3-Core	11 000	110	Yes	Yes	Yes	1921

* Date of manufacture unknown, but prior to 1916.

TABLE 50.

Dimensions of Cables.

(1)	(2)		(3)		(4)		(5)		(6)		(7)	
					Thickness of Dielectric							
No.	Diameter over Lead		Thickness of Lead		Inner Dielectric		Outer Dielectric		Between Conductors		Between Conductor and Lead	
	Single-core Cables.											
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm
1	0·75	1·90	0·08	0·20	0·08	0·2	—	—	—	—	—	—
2	0·95	2·41	0·10	0·25	0·09	0·24	—	—	—	—	—	—
	Concentric Cables.											
3	1·14	2·89	0·13	0·33	0·08	0·2	0·08	0·2	—	—	—	—
4	1·15	2·92	0·09	0·23	0·07	0·18	0·08	0·2	—	—	—	—
5	1·13	2·87	0·13	0·33	0·12	0·3	0·10	0·26	—	—	—	—
6	1·37	3·48	0·11	0·27	0·14	0·35	0·08	0·20	—	—	—	—
7	1·35	3·42	0·09	0·24	0·12	0·3	0·09	0·24	—	—	—	—
8	1·38	3·50	0·08	0·20	0·10	0·25	0·09	0·22	—	—	—	—
9	1·30	3·30	0·10	0·25	0·07	0·18	0·09	0·24	—	—	—	—
10	1·35	3·42	0·09	0·24	0·16	0·4	0·16	0·4	—	—	—	—
	Three-core Cables.											
11	0·43	2·20	0·06	0·15	—	—	—	—	0·06	0·16	0·06	0·16
12	0·90	2·29	0·05	0·13	—	—	—	—	0·31	0·8	0·31	0·8
13	2·23	5·66	0·11	0·28	—	—	—	—	0·25	0·65	0·40	1·0
14	1·23	3·12	0·10	0·25	—	—	—	—	0·10	0·25	0·10	0·25
15	1·69	4·30	0·14	0·35	—	—	—	—	0·24	0·6	0·24	0·6
16	1·81	4·60	0·10	0·25	—	—	—	—	0·24	0·6	0·24	0·6
17	2·56	6·50	0·11	0·28	—	—	—	—	0·37	0·95	0·31	0·8
18	2·60	6·60	0·12	0·30	—	—	—	—	0·40	1·0	0·28	0·7
19	2·52	6·40	0·16	0·40	—	—	—	—	0·35	0·9	0·31	0·8
20	2·48	6·30	0·16	0·40	—	—	—	—	0·35	0·9	0·28	0·7
21	2·50	6·36	0·16	0·40	—	—	—	—	0·37	0·95	0·35	0·9
22	2·40	6·08	0·12	0·30	—	—	—	—	0·35	0·9	0·31	0·8
23	3·19	8·10	0·14	0·35	—	—	—	—	0·43	1·1	0·40	1·0
24	3·06	7·76	0·11	0·28	—	—	—	—	0·40	1·0	0·40	1·0
25	1·83	4·64	0·13	0·32	—	—	—	—	0·16	0·4	0·16	0·4
26	3·07	7·80	0·16	0·40	0·12	0·3	—	—	0·40	1·0	0·40	1·0
27	1·95	4·96	0·11	0·28	—	—	—	—	0·20	0·5	0·20	0·5
28	1·79	4·54	0·13	0·32	—	—	—	—	0·125	0·3	0·17	0·4
29	2·11	5·35	0·14	0·36	—	—	—	—	0·275	0·7	0·20	0·5

TABLE 51.

Particulars of Cables tested in Air laid along the Wood Floor of a Room.

(1)	(2)		(3)	(4)	(5)	(6)		
Cable No.	Sectional Area		Type of Cable	Working Pressure	Armoured	Current for a Rise of 50 deg. F. (27·8 deg. C.)*		
	Nominal	Actual						
			Single-core Cables.					
	sq. in.	sq. in.		volts		amps.	amps.	amps.
1	0·1	0·094	Single-core	660	No	—	190	—
2	0·2	0·196	Single-core	660	No	—	304	—
			Concentric Cables.					
3	0·1	0·108	Concentric	660	Yes	180	—	195
4	0·1	0·099	Concentric	660	No	159	—	167
5	0·1	0·100	Concentric	660	No	161	—	177
6	0·2	0·192	Concentric	660	No	245	—	258
7	0·2	0·196	Concentric	660	No	243	—	265
8	0·2	0·197	Concentric (jute insulated)	660	(Jute covered)	265	—	295
9	0·2	0·205	Concentric	660	Yes	268	—	288
10	0·5	0·480	Concentric	660	No	404	—	460
			Three-core Cables.					
11	0·025	0·029	3-Core	660	No	—	66	—
12	0·05	0·048	3-Core (segmental conductors)	11 000	Yes	—	100	—
13	0·1	0·105	3-Core	6 600	No	—	143	—
14	0·1	0·100	3-Core (segmental conductors)	660	No	—	156	—
15	0·1	0·101	3-Core (segmental conductors)	6 600	Yes	—	158	—
16	0·15	0·150	3-Core (segmental conductors)	6 600	Yes	—	195	—
17	0·15	0·145	3-Core	20 000	Yes	—	208	—
18	0·15	0·145	3-Core	20 000	Yes	—	204	—
19	0·15	0·147	3-Core	20 000	Yes	—	219	—
20	0·15	0·145	3-Core	20 000	Yes	—	208	—
21	0·15	0·144	3-Core	20 000	Yes	—	208	—
22	0·15	0·145	3-Core	20 000	Yes	—	195	—
23	0·2	0·120	{Nos. 23 to 26 are 3-phase split-conductor cables, each 0·2 sq. in. sect. area per phase} 6-Core	20 000	Yes	—	284	—
24	0·2	0·116	6-Core	20 000	Yes	—	264	—
25	0·2	0·208	Twin split	3 300	Yes	—	219	—
26	0·2	0·200	Oval concentric	20 000	Yes	258	—	270
27	0·25	0·250	3-Core	11 000	Yes	—	255	—
28	0·15	0·149	3-Core	3 300	Yes	—	194	—
29	0·15	0·148	3-Core	11 000	Yes	—	211	—

* In the case of concentric cables, the values are given separately for inner and outer conductors; with three-core cables the values are the mean for the three conductors.

APPENDIX II.

Examination of Mie's Formulæ by Mr. S. Butterworth.

In the general case of Mie's formulæ there are n conductors each of radius r, the centres of which are situated at equidistant points on the circumference of a circle of radius a.

The sheath of radius r_4 is concentric with the circle a.

If K is the thermal resistivity of the material between the conductors and sheath, L the length of the cables, and W the thermal resistance, then the first formula given by Mie is

$$W = \frac{K}{2\pi nL} \log_e \frac{1 - \alpha\beta + \sqrt{[(1-\alpha^2)(1-\beta^2)]}}{\alpha - \beta} \quad (49)$$

in which $\alpha = \dfrac{(a+r)^n}{r_4}$ and $\beta = \dfrac{(a-nr)}{(a+nr)} \times \dfrac{(a+r)^n}{r_4}$

The second formula is deduced from (47) upon the assumption that the quantity—

$$1 - \alpha\beta + \sqrt{[(1-\alpha^2)(1-\beta^2)]}$$

is never very different from 2, and may be written

$$W = \frac{K}{2\pi nL} \log_e \frac{r_4}{r_1} \quad . \quad . \quad . \quad . \quad . \quad (50)$$

in which $$r_1 = (a+r)n\sqrt{\frac{nr}{a+nr}} \quad . \quad . \quad . \quad . \quad (51)$$

Formula (50) is identical with that for a cable having a single conductor concentric with the sheath in which r_1 is the radius of the conductor, so that r_1 is the equivalent of the single conductor which would replace the n conductors and give the same thermal resistance between conductor and sheath.

Mie gives the values shown in Table 52 to indicate the agreement of Formulæ (49) and (50).

W_A = value of thermal resistance by Formula (49).
W_B = value of thermal resistance by Formula (50).

$Z = 1 - \alpha\beta + \sqrt{[(1-\alpha^2)(1-\beta^2)]}$, and is equal to 2 when (49) and (50) are in exact agreement.

TABLE 52.

No. of Conductors, n	$\frac{r_4}{a}$	$\frac{a+r}{r_4}$	Z	$\frac{W_B}{W_A}$
2	2·15	0·85	1·78	1·18
2	2·15	0·80	1·84	1·09
3	2·00	0·85	1·91	1·06
3	2·00	0·80	1·93	1·04
4	1·85	0·85	1·94	1·03
4	1·85	0·80	1·96	1·01

Limitations of formulæ.—In the method adopted by Mie, the inner isothermal for which Formula (49) holds is not coincident with the surfaces of the separate conductors, but in the case shown in Fig. 34 consists of the wavy dotted curve shown in the figure, and in the case of a three-core cable may adopt one or other of the forms shown in Fig. 35 according to the relative dimensions of conductors and sheath.

Since the isothermal for which Formula (49) is exact always envelops the conductors, the results given by (49) will always be too low. Mie states that when the conditions approximate to that of Fig. 35A, the error tends to vanish because the isothermal is practically coincident with the conductors. Also, when the conductors approach the sheath and have relatively large radii as in Fig. 35D, the error is again small because the lines of heat-flow are practically confined to the region where the isothermal and conductor surfaces are coincident.

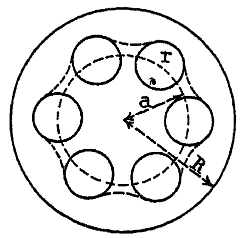

Fig. 34.—Isothermal lines in six-core cable.

By a consideration of the portions of the lines of heat-flow which lie within the isothermal, Mie estimates the maximum error of Formula (49) to be of the order of 5 per cent in the case of a three-core cable.

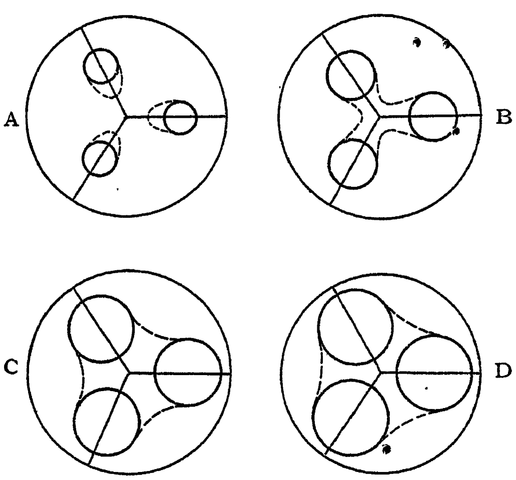

Fig. 35.—Isothermal lines in three-core cable.

It follows, from Table 52, in which Formula (50) is compared with Formula (49), that the error in Formula (50) is less than that indicated by the ratio—W_B/W_A, as W_A is itself less than the true thermal resistance, while the ratio W_B/W_A is greater than unity.

There appears to be no reason to doubt the validity of Formula (50) as applied to cables having three or more conductors, if an inaccuracy of 10 per cent is

permissible in the results. The inaccuracy of the formula is probably not more than 5 per cent.

APPENDIX III.

Experimental Determination of Thermal Resistance by Means of an Electrostatic Analogy.

Thermal resistivity of multi-core cables.

The analogy may be stated in the form :—

$$4\ (\text{Capacity}) = \frac{\lambda K}{\text{Thermal resistance}} \quad . \quad (52)$$

where K = thermal resistivity, and

λ = specific inductive capacity.

If, therefore, a suitable length of metal tube be taken of a size corresponding to the cable sheath, and three or more similar tubes be mounted inside, but electrically insulated from it, in positions corresponding to those of the conductors of a multi-core cable, the apparatus forms a condenser, the capacity of which can be readily determined. By the aid of the relation given above, it then becomes possible to deduce the thermal resistance of the apparatus.

Three cases were tested with the electrostatic model, roughly corresponding to the following three-core cables :—

(1) A cable as used for 20 000 volts.
(2) An 11 000-volt cable.
(3) A 3 300-volt cable.

If a = distance of the centres of the "conductors" from the axis,
r = radius of the "conductors," and
r_4 = inner radius of the containing tube,
then the dimensions actual and relative are as given in Table 53.

Table 53.

Dimensions of Electrostatic Model.

Case	Dimensions of Electrostatic Model					
	Actual			Relative		
	a	r	r_4	a	r	r_4
	cm	cm	cm			
1	2·12	0·73	3·64	0·58	0·20	1·00
2	2·04	0·96	3·64	0·56	0·263	1·00
3	1·695	1·28	3·64	0·46	0·351	1·00

The actual and relative dimensions of the cables referred to above are given in Table 54.

In the capacity tests on the electrostatic models the ratio of the capacity of the three tubes to the outside tube, to that of one of the three tubes placed coaxially to the outside tube, was determined and not the absolute values, which would have necessitated difficult and uncertain corrections for the end effects. The values so obtained were then compared with those obtained by use of each of the formulæ for the ratio derived from Russell's and Mie's formulæ respectively.

The capacity per unit length of two coaxial cylinders of radii r and r_4 is

$$\frac{\lambda}{2\log_e (r_4/r)} \quad . \quad . \quad . \quad . \quad . \quad (53)$$

where λ = specific inductive capacity.

Table 54.

Dimensions of Three-core 0·15 *sq. in. Cables.*

Working Pressure	Dimensions of three 3-core 0·15 sq. in. Cables					
	Actual			Relative		
	a	r	r_4	a	r	r_4
volts	cm	cm	cm			
20 000	1·33	0·65	2·76	0·48	0·236	1·00
11 000	1·15	0·65	2·325	0·495	0·280	1·00
3 300	0·90	0·65	1·95	0·463	0·334	1·00

The capacity of three tubes of radius r placed symmetrically at a distance a from the axis of the surrounding tube is, according to Russell,

$$\frac{3\lambda}{2\log_e [(r_4^6 - a^6)/(3r_4^3a^2r)]} \quad . \quad . \quad . \quad (54)$$

Therefore q_R, the ratio of the capacities according to Russell, is

$$q_R = \frac{\text{Capacity with 3 eccentric tubes}}{\text{Capacity with 1 coaxial tube}}$$

$$= \frac{3\log_e (r_4/r)}{\log_e [(r_4^6 - a^6)/3r_4^3a^2r]} \quad . \quad . \quad . \quad (55)$$

According to Mie, the capacity of three eccentric tubes is

$$\frac{3\lambda}{2\log_e\left[\left\{(1-\alpha\beta) + \sqrt{(1-\alpha^2)(1-\beta^2)}\right\}/(\alpha-\beta)\right]} \quad (56)$$

where $\alpha = \dfrac{(a + r^3)}{r_4}$ and $\beta = \dfrac{(a - 3r)}{(a + 3r)}\,\alpha$

and therefore q_M, the ratio of the capacities according to Mie is

$$q_M = \frac{\text{Capacity with 3 eccentric tubes}}{\text{Capacity with 1 coaxial tube}}$$

$$= \frac{3\log_e (r_4/r)}{\log_e\left[\left\{(1-\alpha\beta) + \sqrt{(1-\alpha^2)(1-\beta^2)}\right\}/(\alpha-\beta)\right]} \quad (57)$$

In Table 55 the following ratios are given for the three cases of the electrostatic model considered :—

(*a*) The ratio of the capacities of one inner to that of three inner tubes by experimental determination, q.
(*b*) The ratio of the same capacities determined by the Russell formula, q_R.
(*c*) The ratio of the same capacities determined by the Mie formula, q_M.

The thermal resistances are proportional to the reciprocals of the capacities of cables of similar dimensions; thus the ratios of the thermal resistances will be the inverse of the ratios of the capacities given above, and the errors will be of opposite sign and must be corrected for numerical value, e.g. minus 29 becoming plus 41 per cent.

TABLE 55.

Comparison of Ratios determined experimentally and by Russell's and by Mie's Formulæ.

Case	q	q_R	q_M	Error of q_R and q_M referred to q	
				q_R	q_M
				per cent	per cent
1	3·356	3·107	3·576	− 7·5	+ 6·7
2	3·465	2·925	3·775	− 15·7	+ 9·0
3	2·975	2·11	3·335	− 29·0	+ 12·1

In the calculation of thermal resistivity K from a determined value of thermal resistance, the relation assuming Russell's formula is

$$K = \frac{6\pi(t_1 - t_2)}{nI^2 r_4 \log_e [(r_4^6 - a^6)/3r_4^3 a^2 r]} \quad . \quad . \quad (58)$$

where t_1 and t_2 are the temperatures of conductor and sheath respectively, and, since the modulus of this expression is usually too great, the value of thermal resistivity determined by means of it is too small.

Hence, taking a cable having an actual thermal resistivity of 500, the values deduced by the two formulæ would be those given in Table 56.

TABLE 56.

Comparison of Thermal Resistivities of Three-core Cables.

Working Pressure	20 000 V	11 000 V	3 300 V
Method	Model (1)	Model (2)	Model (3)
By experiment ..	500	500	500
By Russell	464	432	388
By Mie	533	555	570

Russell's formula is the more convenient and, if the correcting factor be known and applied, values obtained by means of it can be regarded as having a satisfactory degree of accuracy for the higher-pressure cables. In view of its greater simplicity its use was preferred in these cases.

As a result of the experimental work a curve was drawn (see Fig. 36) showing the errors of the Russell formula; it will be seen that for the lower-pressure cables the error appears to become indefinitely large, and for such cases Mie's formula with its smaller error was preferred.

Effect of the lay on the capacity of the electrostatic model.—It was suggested by Dr. A. Russell that the lay of the conductors of the cable might have some effect on the thermal resistance, and an experimental determination of the effect of the lay was therefore made with the electrostatic model. Its capacity was measured with three 1·46-cm diameter "conductors" placed at 1·9 cm distance from the axis, and the values for two "conductors" for the following cases are given in Table 57:

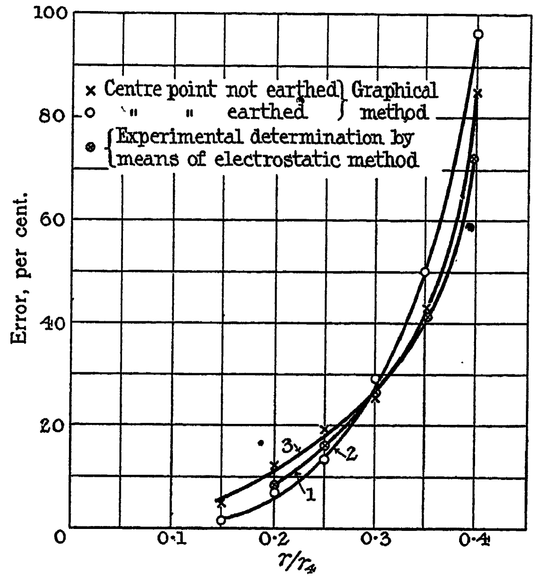

FIG. 36.—Thermal resistance of three-core cable with circular conductors. Error in Russell's formula expressed as a function of the ratio of the radius of the conductor to the inner radius of the lead sheath.

(1) With "conductors" parallel to cable axis.
(2) With one end of the model rotated through 60°, corresponding to a pitch of about 480 cm.

TABLE 57.

Comparison of Capacities of Electrostatic Model with "Conductors" parallel to Cable Axis and with One End rotated through 60°.

Capacity	Case 1	Case 2
Leads + tubes	560	519
Leads	86	86
Tubes only	474	433

Thus there was a reduction of 8·7 per cent due to the rotation.

The tubes, however, in (2) do not form a true helix, since they remain straight. The effect of the rotation of the ends, therefore, is to cause the centres of the

tubes to close in on one another. This fact would in itself reduce the capacity, and the extent of this reduction must be taken into account.

The mean distance of conductor centres from the axis at the ends of the model was 1·87 cm.

At the middle portion of the conductors in the twisted condition the mean distance was by measurement, 1·61 cm.

The ratio of the capacities for two cases in which $a_1 = 1{\cdot}87$ and $a_2 = 1{\cdot}61$ respectively, with $r = 0{\cdot}73$ and $r_4 = 3{\cdot}65$, according to the Russell formula,

$$= \frac{\log [(r_4^6 - a_1^6)/3r_4^3 a_1^2 r]}{\log [(r_4^6 - a_2^6)/3r_4^6 a_2^2 r} = \frac{0{\cdot}9306}{0{\cdot}7950} \quad . \quad . \quad (59)$$

This minimum distance, however, refers only to the middle portion of the tubes. If, as an approximate assumption, the reduction of capacity is taken as being, therefore, only one-half, this gives 8·5 per cent as the reduction of capacity to be expected on account of the closing in of the middle portions of the tubes, an amount which does not greatly differ from the 8·7 per cent reduction indicated by the experimental determinations. The reduction of capacity in case (2) as compared with (1) is therefore completely explained by the closing-in effect and leaves nothing to be referred to the effect of the lay.

It should be noted that the pitch in the model was about 480 cm, which does not necessarily correspond to the pitch in a cable as manufactured. The experiment, however, does suggest that there is little, if any, difference due to the lay.

APPENDIX IV.

Calculation of the Thermal Resistance of Three-core Cables, and Examination of Russell's Formula by Mr. E. B. Wedmore.

The N.P.L. results given in Appendix III cover only a portion of the ground, and with a view to extending the work to cover all cases which may arise, and as a check on previous work, the problem was attacked afresh by a geometrical method described below.

It is shown that the results obtained by the geometrical method are in agreement with those obtained by the experimental tests made. The method has the advantage that it is applicable with equal facility to conductors of any shape, for example, of shapes incapable of simple mathematical expression such as D-shaped and segmental conductors.

The intention is to extend to three-core cables by calculation the results readily obtained for single-core cables. It should be noted, however, that the assumption has been made that the thermal resistivity of the dielectric is the same throughout the section, whereas the material surrounding the cores and next the sheath may differ from that used to pack the odd-shaped spaces between. If, however, this is known to be the case, a correction can be made by the geometrical method but not by any other.

Geometrical method.—The method is shown by an example in Fig. 37. The three conductors in the cable are symmetrically placed and therefore it is only necessary to deal with one of them and its sector of 120°. The lines of heat-flow are shown flowing from the conductor to the sheath. The latter is shown by a heavy full line. Isothermals are shown at right angles to the lines of flow.

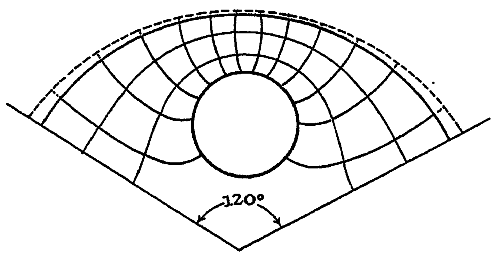

Fig. 37.—Geometrical construction for determining the thermal resistivity of a three-core cable.

The method of construction is as follows:—

(*a*) A certain number is chosen for the lines of heat-flow, in this case 12 per conductor.

(*b*) A rough attempt is made to place these lines and the isothermals, the scale for the isothermals being based on the assumption that the intersections will form squares. This is an arbitrary but convenient scale.

(*c*) The attempt is made and checked on the basis of the following.

(i) The surfaces of the conductors and sheath respectively are isothermals.

(ii) The lines of heat-flow must be everywhere at right angles to the isothermals.

(iii) The intersections must tend to form squares. (Although some of the figures shown are far from square, it will be seen that if intermediate lines of flow and isothermals were inserted they would become more nearly square and, in the limit, the four angles being right angles and the curvature of the sides infinitesimal, they become squares.)

(*d*) A diagram which complies with the above as nearly as can be judged by eye may then be scaled with dividers and an average correction factor worked out. In the case of the diagram shown in Fig. 37, the correction factor worked out at zero, the positive and negative errors cancelling, but in other diagrams a correction of from 1 to 4 per cent was required.

(*e*) The thermal resistivity on the arbitrary scale is shown by the number of isothermals, and to estimate the fraction an imaginary extension is made beyond the sheath to complete the outermost row of squares as shown by the dotted line in Fig. 37. The number is estimated at 2·77, which represents the thermal resistance x between one conductor and the sheath.

(*f*) The corresponding thermal resistance is obtained for a single conductor concentric with the sheath, or may be worked out by the following formula, in which it is assumed that there are 12 lines of heat-flow as in the case considered above.

$$\text{Thermal resistance} = 4 \cdot 40 \log_{10} \frac{r^4}{r} \quad . \quad . \quad (60)$$

(*g*) If the thermal resistivity of part of the dielectric is higher or lower than that of the remainder, the geometrical construction must be modified so that the intersections, instead of being squares, are parallelograms in which the distance between isothermals is proportionately reduced or increased.

Results obtained.—The following quantities are used by Mr. Melsom :—

a = distance of centre of conductor from centre of cable.
r = radius of conductor.
r_4 = inner radius of sheath.

The thermal resistance is independent of the absolute dimensions and depends only upon the relative values

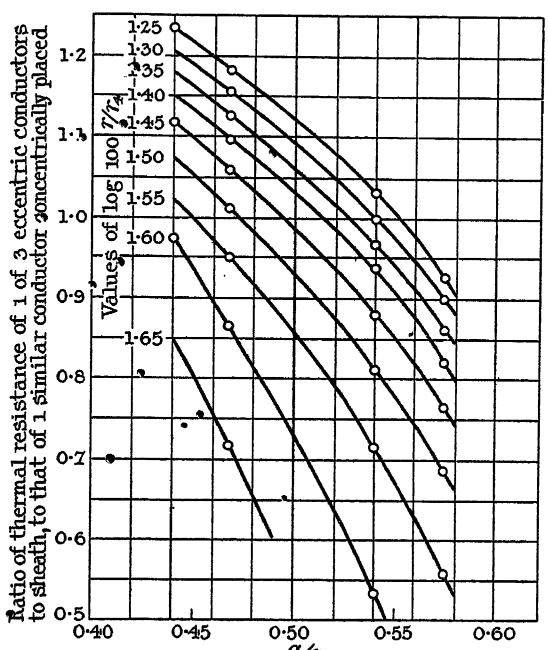

FIG. 38.—Curves for deducing thermal resistances of three-core cables from those of single-core cables.

of a, r and r_4. With $a/r_4 = 0 \cdot 54$, five cases were worked out with different values of r, and a sixth, the limiting case, in which, r/r_4 being $0 \cdot 46$ and $r/r_4 + a/r_4 = 1$, the conductor touches the sheath. A curve was drawn for this. Three cases were then worked out for each of two other values of a, and further curves drawn through these, with the corresponding zero values.

From these, curves were drawn showing the relationship between the three, from which were finally deduced the curves shown in Fig. 38.

In Fig. 38 the vertical scale gives the ratio between the thermal resistance of one of three eccentric conductors to sheath, to that of a similar conductor concentrically placed. The resistance of three conductors to sheath would be one-third of this.

The horizontal scale gives values of a/r_4, and the curves each correspond to a particular value of $\log (100r/r_4)$, which gives a convenient unit, and the values being in equal steps intermediate values are readily obtained by interpolation.

From these curves the thermal resistance of any three-core cable can be worked out from the corresponding thermal resistance of a single-core cable of the same dimensions of sheath and conductor.

Comparison of results.—In Table 58 are given the results of calculations of the cases tested by means of capacity measurements, showing the relative values for eccentric and concentric conductors, bearing in mind that the capacities are inversely proportional to the thermal resistances.

TABLE 58.

Relative Thermal Resistances of Concentric Conductors and Relative Capacities of Eccentric Conductors deduced from the Geometrical Method.

Case	Dimensions of Test Pieces			$\log \frac{100r}{4}$	Relative Thermal Resistances, One Conductor, from Curves, Fig. 38	Relative Capacities, Three Conductors
	a	r	r_4			
	cm	cm	cm			
(1)	0·58	0·20	1·00	1·300	0·880	3·41
(2)	0·56	0·263	1·00	1·420	0·848	3·54
(3)	0·46	0·351	1·00	1·545	0·976	3·07

In Table 59 is shown a comparison of the relative results from tests made at the N.P.L. and those obtained by the geometrical method.

TABLE 59.

Comparison between the Results deduced from the Geometrical Method and the Capacity Tests.

Case	Geometrical Method (Table 58) (a)	Capacity Tests (Appendix III) (b)	Ratio a/b
(1)	3·41	3·356	1·02
(2)	3·54	3·465	1·02
(3)	3·07	2·970	1·03

Accuracy obtainable.—In the N.P.L. tests (Appendix III) there are certain corrections applying to both single-core and concentric cables, such that the series of ratios worked out are probably more accurate than the measurement of the individual capacities. The above results are in conformity with this, and it is thought that the actual figures obtained from the

curves here given are at least as accurate as those obtained by the tests made by the electrostatic method.

With any size and form of cable now made, and on the assumption of uniform thermal resistivity of the dielectric and uniform temperature throughout the surface of the conductor, and again of the sheath, one should obtain results correct to within ±2 per cent. If the material used as packing differs in thermal resistivity the error should not be more than 5 per cent with any materials proper for the purpose. These are only estimated figures, but are thought to be safe.

APPENDIX V.

TABLE 60.

Moisture Content of the Soil in the Newcastle-upon-Tyne district.

Nature of Soil	Nature of Surface	State of Surface	Date taken	Depth taken	Moisture
					per cent
Stiff plastic clay	Macadam	Wet	8/7/20	2 ft. 0 in.	13·7
Brown sandy clay	Macadam	Wet	8/7/20	1 ft. 0 in.	18·8
Dark brown clay and loam	Shale	Wet	11/7/20	1 ft. 6 in.	14·1
Dark brown stiff clay	Shale	Wet	11/7/20	3 ft. 0 in.	15·2
Dark clay with many small pebbles ..	Macadam	Wet	15/7/20	3 ft. 0 in.	19·3
Bright red plastic clay with much oxide of iron	Unmade	Wet	23/7/20	7 ft. 0 in.	44·1
Stiff brown clay and loam	Grass	Dry	12/8/20	0 ft. 3 in.	15·1
Brown plastic clay	Grass	Dry	12/8/20	3 ft. 0 in.	20·9
Cindery soil	Macadam	Dry	22/10/20	1 ft. 0 in.	19·8
Cindery soil	Macadam	Dry	22/10/20	2 ft. 0 in.	21·3
Stiff plastic clay	Tarmac	Wet	9/11/20	2 ft. 6 in.	22·5
Stiff plastic clay	Tarmac	Wet	9/11/20	3 ft. 6 in.	23·0
Loamy with much clay and sand ..	Grass	Dry	15/11/20	1 ft. 3 in.	23·8
Yellow plastic clay, much sandstone ..	Grass	Dry	15/11/20	2 ft. 6 in.	25·0
Stiff yellow plastic clay	Grass	Wet	6/12/20	0 ft. 3 in.	25·3
Soft grey, plastic clay with vegetable fibres	Grass	Wet	6/12/20	2 ft. 0 in.	26·7
Brown clay with much cindery soil ..	Macadam	Wet	1/12/20	2 ft. 0 in.	18·2
Very soft dark clay	Grass	Wet	9/12/20	5 ft. 6 in.	33·5
Heavy dark plastic clay	Grass	Wet	9/12/20	9 ft. 0 in.	38·7
Sand and pebbles	Tarmac	Dry	1/7/21	2 ft. 6 in.	8·8
Stiff yellow plastic clay	Fine ashes	Dry	1/7/21	1 ft. 8 in.	21·6
Dark plastic clay and some stones ..	Square sets	Dry	8/7/21	2 ft. 5 in.	2·5
Stiff brown plastic clay	Macadam	Dry	26/7/21	2 ft. 0 in.	28·1
Loamy soil with much clay	Macadam	Dry	26/7/21	1 ft. 0 in.	12·6
Clayey loam and some cinders ..	Square sets	Dry	13/7/21	2 ft. 6 in.	16·5
Dark soil, cinders and building refuse ..	Ashes	Dry	27/7/21	0 ft. 6 in.	8·2
Dark soil, cinders and building refuse ..	Ashes	Dry	27/7/21	2 ft. 0 in.	12·1
Cindery waste and some clay	Ash footpath	Damp	18/8/21	0 ft. 6 in.	19·1
Brown clayey loam	Ash footpath	Damp	18/8/21	1 ft. 6 in.	15·5
Yellow sand	Unmade	Dry	27/8/21	2 ft. 6 in.	3·8
Yellow sand	Grass	Dry	27/8/21	3 ft. 6 in.	5·5

APPENDIX VI.

DETERMINATION OF THE EMISSIVITY OF LEAD SHEATHS BY MR. J. F. WATSON.

For the purpose of the tests, four lengths of quite new lead sheath each 9 ft. in length and of varying diameters were obtained. These were mounted singly on a board placed along trestles and raised on blocks of wood 2 in. above the board. The ends were knocked up flat and connections made with the current leads by means of copper bolts. The dimensions of the lead sheaths are given in Table 61.

The sheaths were first tested as received, clean and bright. Care was taken to keep the doors and windows shut during the tests in order to exclude draughts. The results of the tests are given in Table 62.

The lead sheaths were then painted dull black and tested as before. The results of these tests are given in Table 63.

The mean value of the emissivity constant h (watts per degree C. per cm^2) for the bright sheath is 0·00070 and for the black sheath 0·00107.

TABLE 61.

Dimensions and Resistance of the Lead Sheaths.

No. of Lead Sheath	Total Length	Length between Potential Wires	Diameter over Sheath	Surface Area of Sheath per cm	Thickness of Sheath	Resistance of Sheath	Sectional Area	
							Lead Sheath	Copper of Equal Resistance
	ft.	ft.	in.	cm²	in.	ohm	sq. in.	sq. in.
1	9	6	3·30	26·30	0·170	0·00037 at 12° C.	1·74	0·133
2	9	6	1·75	14·00	0·110	0·00110 at 20° C.	0·58	0·045
3	9	6	1·20	9·50	0·0900	0·00180 at 20° C.	0·31	0·024
4	9	6	2·30	18·30	0·135	0·00066 at 20° C.	0·93	0·070

TABLE 62.

Heating Tests on Bright Lead Sheaths.

No. of Lead Sheath	Current	Power Expended		Temperature		Calculated Temperature-rise for Uniform h	Emissivity Constant, h		
		Per ft.	Per cm	Starting	Rise		For Each Test	Mean for Each Test	Mean for Series
	amps.	watts	watts	° C.	deg. C.	deg. C.			
1	300	17·70	0·580	12·0	30·7	31·8	0·00072	0·00069	0·00070
	400	10·95	0·360	—	21·1	19·5	0·00065		
	300	6·00	0·197	—	13·7	10·7	0·00055		
	250	4·10	0·134	—	7·3	7·3	0·00069		
2	150	4·35	0·142	20·6	13·8	14·5	0·000734	0·000714	
	125	3·00	0·098	—	10·1	10·0	0·000692		
	100	1·88	0·062	—	6·1	6·3	0·000734		
3	80	2·06	0·068	19·2	10·0	10·2	0·000708	0·000708	
	70	1·56	0·051	—	7·6	7·7	0·000709		
	60	1·14	0·036	—	5·3	5·4	—		
4	280	9·52	0·313	20·9	24·9	24·7	0·000680	0·00069	
	240	6·88	0·225	—	18·0	17·6	0·000683		
	200	4·65	0·153	—	11·9	11·9	0·000700		

TABLE 63.

Heating Tests on Black Lead Sheaths.

No. of Lead Sheath	Current	Power Expended		Temperature		Calculated Temperature-rise for Uniform h	Emissivity Constant, h		
		Per ft.	Per cm	Starting	Rise		For Each Test	Mean for Each Test	Mean for Series
	amps.	watts	watts	° C.	deg. C.	deg. C.			
1	400	10·580	0·346	—	13·7	12·0	0·00096	0·00092	0·00107
	300	5·850	0·192	13·2	7·7	6·6	0·00095		
	200	2·41	0·079	—	3·5	2·7	0·00086		
2	150	4·270	0·140	—	8·6	9·1	0·00116	0·00112	
	125	2·940	0·097	19·8	6·0	6·3	0·00115		
	100	1·870	0·061	—	4·1	4·0	0·00106		
3	120	4·740	0·155	—	14·6	14·8	0·00112	0·00111	
	80	2·030	0·067	19·0	6·3	6·4	0·00111		
	70	1·560	0·057	—	4·8	5·0	0·00112		
	60	1·135	0·037	—	3·6	3·6	0·00110		
4	280	9·170	0·300	—	14·5	14·7	0·00113	0·00113	
	240	6·650	0·218	19·5	10·8	10·9	0·00111		
	200	4·45	0·149	—	7·1	7·4	0·00115		

APPENDIX VII.

Determination of Thermal Resistance of Multi-core Cables with Segmental Conductors.

In considering the question of the calculation of the thermal resistivity of three-core cables with segmental conductors, it was found that the construction did not lend itself to mathematical treatment. Experiments were therefore carried out with an electrostatic model somewhat on the same lines as those for three-core cables with circular conductors.

The exact shape of the conductors was not known, but a model was made in accordance with dimensions supplied by Mr. J. F. Watson, with the additional assumption that the overall area (i.e. copper + interstices in the strand) of the segmental conductor was the same as that of the circular conductor. In view of the fact that in some cases the segmental conductors are hammered and rolled, this assumption is not altogether justified, but this does not affect the experimental results appreciably.

Shaped wooden models of a segmental conductor cable corresponding to a 0·25 sq. in. three-core cable

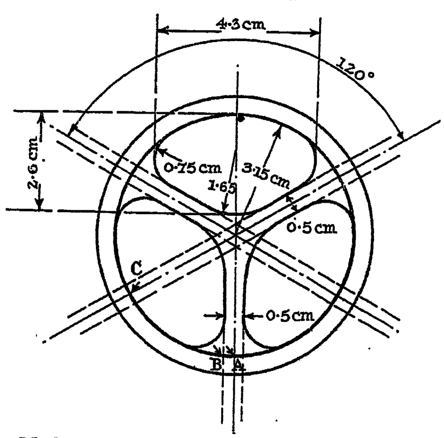

Fig. 39.—Model of three-core cable with segmental conductors, corresponding to a 660-volt cable.

were made and covered with tinfoil (see Fig. 39). These were mounted in a brass tube of internal diameter 7·3 cm, and the capacity of the apparatus was measured. The results were as follows :—

Three segments in parallel + leads ..	320·1 $\mu\mu$F
Leads only	17·4 $\mu\mu$F
∴ Three segments only	302·7 $\mu\mu$F

Tinfoil was then wrapped round the three segments whilst still mounted in the position of the previous test so as to form an approximately cylindrical shape enclosing the segments and the capacity was again measured. The results were as follows :—

Tinfoil cylinder + leads	337·0 $\mu\mu$F
Leads only	17·3 $\mu\mu$F
∴ Tinfoil cylinder only	319·7 $\mu\mu$F

Ratio of capacity of segments to that of cylinder $= \frac{302\cdot 7}{319\cdot 7} = 0\cdot 945$.

The effective parts of the segments were assumed to be those directly facing the containing cylinder. The ratio of these (see Fig. 39) was (arc CB)/(arc CA) and this in the model was $12/13 = 0\cdot 923$.

It therefore follows that the thermal resistance of a cable of this type can be calculated to an accuracy of 2 or 3 per cent by assuming that the heat flows radially from an inner cylinder, except where the three gaps occur, to the outer containing cylinder. The process of calculating the thermal resistance of such a cable would therefore resolve itself into calculating the resistance between the outer cylinder and an inner cylinder which just touched the outer surfaces of the segments, and then increasing the result in the ratio (arc CA)/(arc CB).

The case just considered was a specially favourable one, as the general dimensions corresponded to a 660-volt cable and the gap between the segments was small. The same three shaped segments were therefore mounted in a larger tube of 10·1 cm diameter so as to make the general dimensions correspond to a 6 600-volt cable. The segments were placed so that the distance of the front of the segment from the surrounding cylinder was

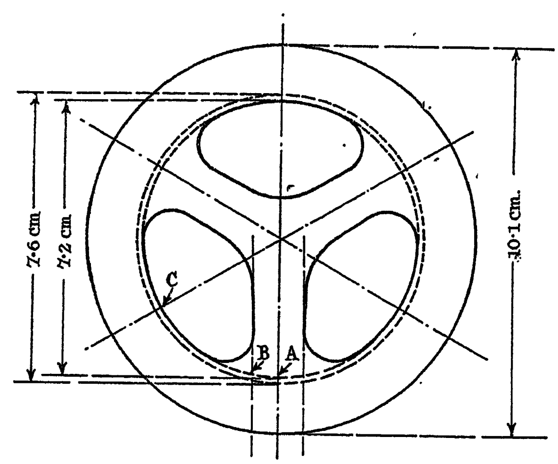

Fig. 40.—Model of three-core cable with segmental conductors, corresponding to a 6 600-volt cable.

equal to the distance between the flat sides of the neighbouring segments. With this arrangement, the front circular faces of the segments lay somewhat outside their proper positions (see Fig. 40), but this could have no appreciable effect on the general result. The capacity of the three segments in parallel to the outside containing cylinder was then measured, and the results were as follows :—

Segments + leads	147·5 $\mu\mu$F
Leads only	17·7 $\mu\mu$F
∴ Segments only	129·8 $\mu\mu$F

Instead of surrounding the segments with tinfoil they were replaced by a brass tube of the same length as the segments and 7·6 cm external diameter. The capacity was then measured and the results were as follows :—

Cylinder + leads	.. ..	193·9 $\mu\mu$F
Leads only	.. .. ..	17·3 $\mu\mu$F
∴ Cylinder only	.. ..	176·6 $\mu\mu$F

The cylinder was, however, somewhat larger than a cylindrical surface that would just contain the segments, the diameter of which would be 7·2 cm. The capacity of the apparatus with this cylinder was therefore reduced in the ratio of—

$$\log (10\cdot 1/7\cdot 6) \text{ to } \log (10\cdot 1/7\cdot 2) = 0\cdot 840$$
$$\text{The capacity} = 176\cdot 6 \times 0\cdot 840 = 148\cdot 4$$
$$\text{and the ratio} = 129\cdot 8/148\cdot 4 = 0\cdot 875 = 7/8$$

The ratio of the effective surface of the segments to that of the containing cylinder, namely, (arc CB)/(arc CA) in the second case is 8·7/10·7 = 0·81, and there is a discrepancy of 7·4 per cent between the measured values and those calculated by the proposed rule.

With an 11 000-volt cable the difference would of course be larger, but a method of this kind with the readily obtained correcting factor would be simple and easily applied. The question of exact dimensions is, however, important; there is a large difference between the dimensions of the finished cable supplied by two cable makers, and, further, these do not permit of evaluation of the only dimension which appears to be important for the purpose, i.e. the shape and size of a segmental conductor of a given sectional area. It would appear that there should be no great difficulty in obtaining the necessary dimensions, since the segmental conductor must in practice be rolled or hammered to a given shape, which is as nearly as practicable a segment.

It should be clear that the case given above is most favourable to the method; with smaller conductors and when the proportion of copper to paper is less the correction would probably be larger.

It is useful to consider the amount of possible difference in rating between a segmental and a circular conductor cable, and one or two cases have therefore been worked out for comparison, the value of thermal resistance being based on the method described above.

In view of the absence of standard dimensions for such cables, it was decided that a comparison should be made between three-core cables having circular conductors and those with segmental conductors, on the assumption in the latter case that the conductor and the belt insulation make up a true segment of a circle, thus not allowing for rounding off the conductor. It is clear that this is not a practical case, but a value based on it represents the extreme for this type of cable. The value for an actual cable will lie somewhere between this and that for the corresponding cable with circular conductors, depending on the exact shape of the segmental conductors.

The further assumptions made and the method of calculation are as follows:—

TABLE 64.

Thermal Resistance of Three-core Armoured Cables laid Direct in the Ground.

	660 volts		2 200 Volts		3 300 Volts		11 000 Volts	
	Circular Conductors	Segmental Conductors	Circular Conductors	Segmental Conductors	Circular Conductors	Segmental Conductors	Circular Conductors	Segmental Conductors
				0·25 sq. in.				
S_1	29	17·7	34·2	23·1	24·7	17·7	37·7	34·3
S_2	17·2	20	17·6	19·1	17·2	18·5	14·0	15·7
G_{10}	41·3	42·8	40·6	42·4	49·2	50·9	46·8	48·2
I_{50}	389	402	376	392	374	386	357	361
				0·1 sq. in.				
S_1	34·7	24·1	44·2	33·4	32·3	26·5	47·5	48·8
S_2	21·7	23·5	20·2	22·1	19·5	21·7	17·2	17·4
G_{10}	44·8	46·3	44·0	45	52·5	53·6	49·2	50·3
I_{50}	229	238	222	230	223	229	213	214

S_1 = thermal resistance per unit length of cable between conductors and sheath.
S_2 = thermal resistance per unit length of cable between the lead sheath and the outer surface of the armouring and protective coverings.
G_{10} = thermal resistance of the soil in this case based on sandy loam having a moisture content of 10 per cent.
I_{50} = current for a temperature-rise of 50 degrees C.

General Method of calculating Cables having Segmental Conductors.

(*a*) The values for cables with segmental conductors are calculated on the assumption that the conductors are true segments having the same overall area of cross-

section (i.e. copper plus interstices in the strand) as the corresponding circular conductors.

(*b*) The further assumption is made that the heat flows radially from the circular parts of the segment faces and that there is no flow from the side faces. The thermal resistance of a cable with segmental conductors is thus equal to that of a single-core cable with the same thickness of dielectric, multiplied by a factor which allows for the effect of the three inoperative portions, i.e. multiplying by the factor

$$\theta = \frac{\text{length of arc AC}}{\text{length of arc AB}} \text{ (see Fig. 41)}$$

If r be taken as the radius of the cylinder formed by

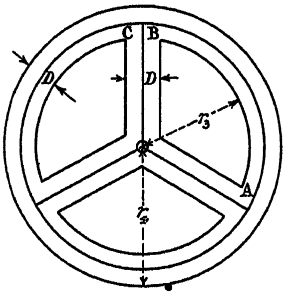

FIG. 41.—Representation of segmental conductor cable.

the three partial conductor segments, and d the overall diameter of the circular conductor of equivalent size,

$$r = \frac{D + \sqrt{(D^2 + 3{\cdot}28d^2)}}{2{\cdot}09} \quad . \quad . \quad (61)$$

and the factor $\dfrac{\text{Arc CA}}{\text{Arc CD}} = \theta = \dfrac{r}{r + 0{\cdot}77D} \quad . \quad . \quad (62)$

Eight sizes of cable have been compared and the values of the various components of the thermal resistance are given in Table 64, side by side, in order to facilitate comparison.

The results show that the difference between the current-carrying capacity of cables of the sizes considered, having circular and segmental conductors respectively, is in general negligible, and in the extreme case only about 4 per cent.

APPENDIX VIII.

THERMAL RESISTIVITY OF CHALK SOIL.

In view of the large difference between the values of thermal resistivity of sandy loam and clay soils, it was desirable to obtain values for a third type of soil, and tests were made on samples of crushed chalk supplied by Mr. J. Christie. The values obtained are given in Fig. 5 and Table 30. It will be noted that while the value for chalk in the dry condition is higher than that for either gravel or clay, the addition of water results in a series of values intermediate between the other two, the value of 90 with a moisture content of 19 per cent being identical with that of sandy loam with 15 per cent of water.

APPENDIX IX.

GRAPHICAL REPRESENTATION OF SELECTED LOAD TABLES.

For the purpose of the preparation of a summary of the report in a form convenient for reading at the meetings of the Institution, a number of the load tables were plotted so that the differences of loading due to the various factors mentioned in the report could be readily appreciated. These are now included in accordance with the request of several members who contributed to the discussion.

Fig. 42 refers to 3 300-volt three-core armoured cables laid direct in the ground, for the four values of thermal resistivity of the soil g. The values for the tables published by the Verband Deutscher Electrotechniker are given for comparison. It will be seen that the German values when corrected to the same temperature-rise are somewhat higher than the British; further, it should be noted that the German values refer to two cables laid in a trench, while the British refer to one cable only. When two cables are laid in one trench at a distance apart of 8 inches, the British values must be reduced to 0·82 of the figures in the curves, and thus the difference between the British and German values would be considerably greater.

Fig. 43 is a similar series of values for an 11 000-volt cable.

The effect of varying thickness of dielectric when cables are laid direct in the ground is shown in Figs. 44 and 45, one set of curves referring to three-core cables with the centre point earthed, and the other not earthed. Fig. 46 gives a similar set of values for concentric cables.

Fig. 47 is a comparison of 660-volt cables, single, concentric and three-core when laid direct in the ground.

Figs. 48 and 49 show the values for concentric and three-core armoured cables when in air, free from draughts. It will be noted that in these cases the order of the curves is not the same as when the cables are buried direct in the ground (see Figs. 44 and 45). The reason is, of course, that in the air condition the increase in thickness of the dielectric in some cases is more than compensated for by the additional radiating surface.

Fig. 50 gives values for 660-volt cables, single, concentric and three-core in air.

Figs. 51, 52, and 53 are curves for three-core cables of different pressures under the three conditions, i.e. in air, buried direct in the ground, and drawn into ducts.

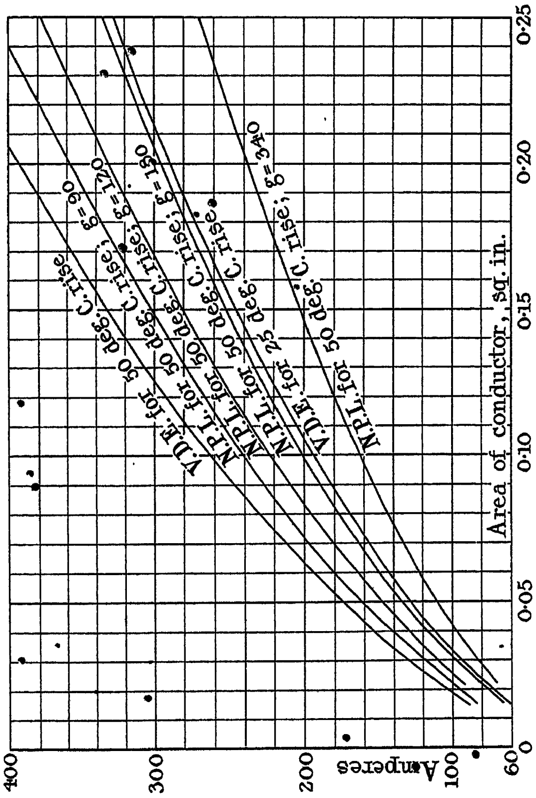

FIG. 42.—3 300-volt 3-core armoured cables laid direct (not earthed).

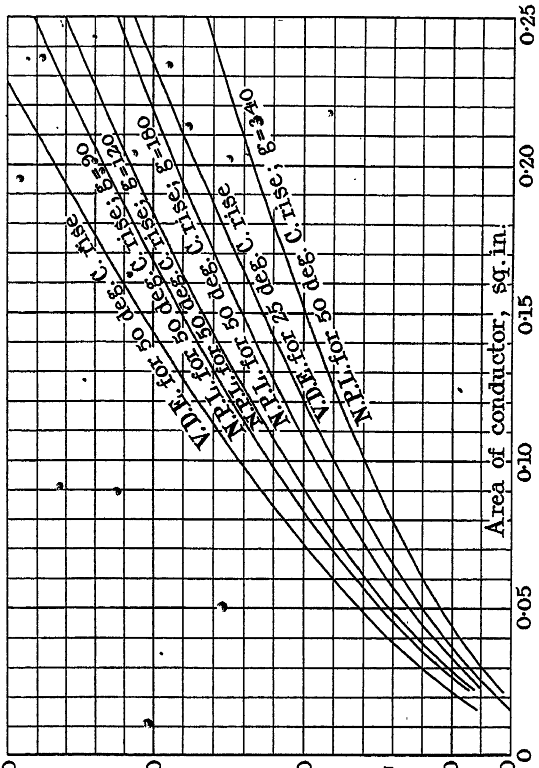

FIG 43.—11 000-volt 3-core armoured cable laid direct (not earthed).

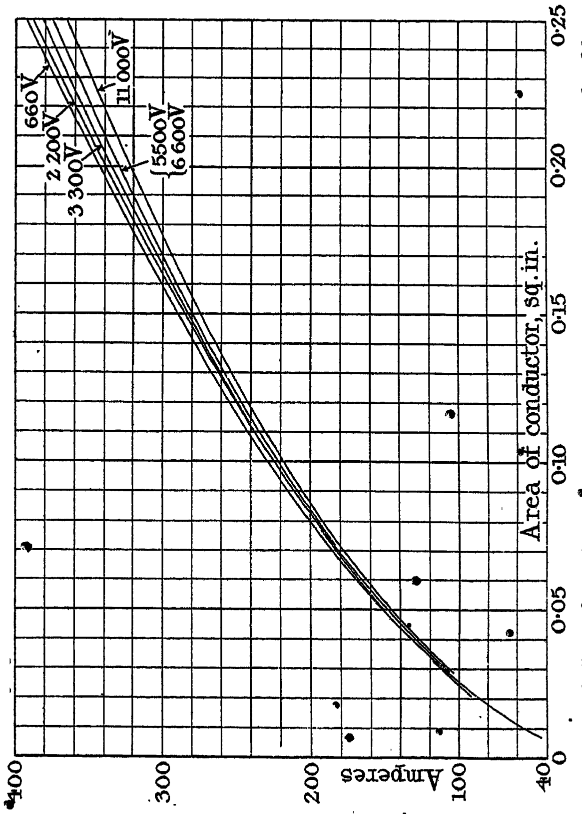

Fig. 44.—Effect of varying thicknesses of insulation of 3-core armoured cables laid direct (earthed). $g = 120$.

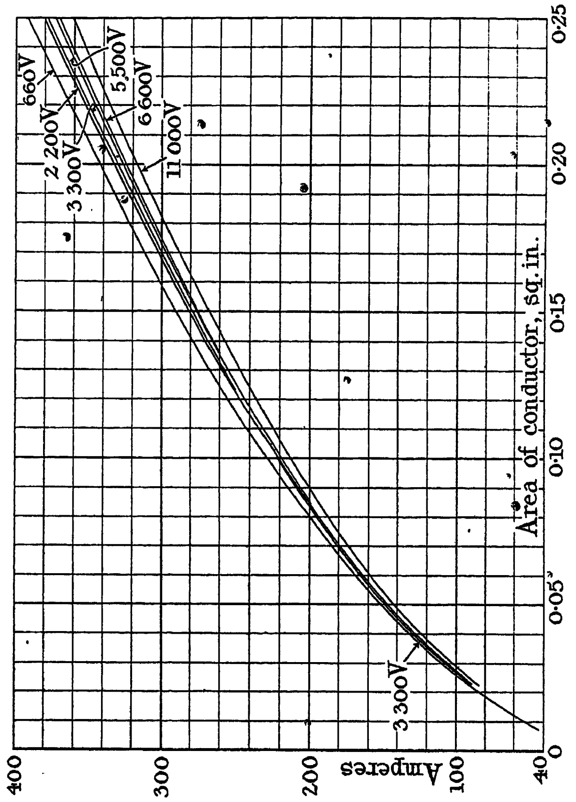

Fig. 45.—Effect of varying thicknesses of insulation of 3-core armoured cables laid direct (not earthed). $g = 120$.

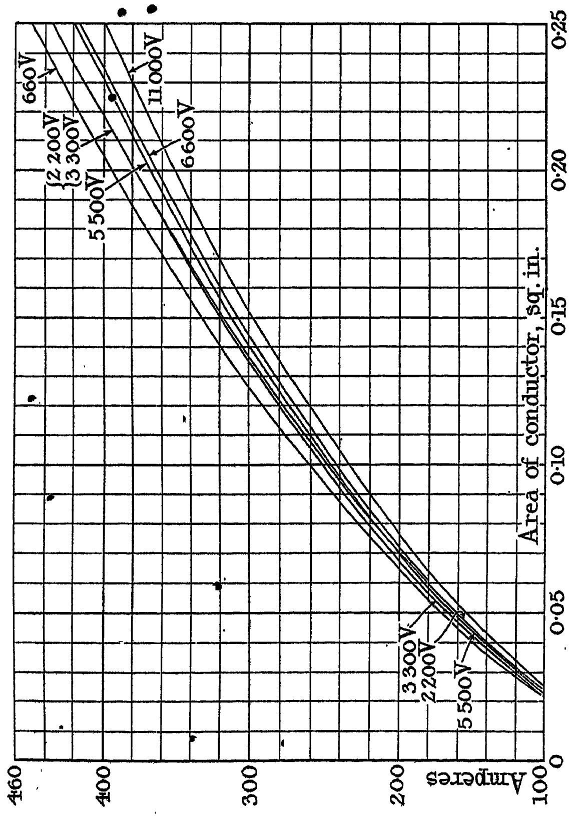

Fig. 46.—Effect of varying thicknesses of insulation of armoured concentric cables (not earthed). $g = 120$.

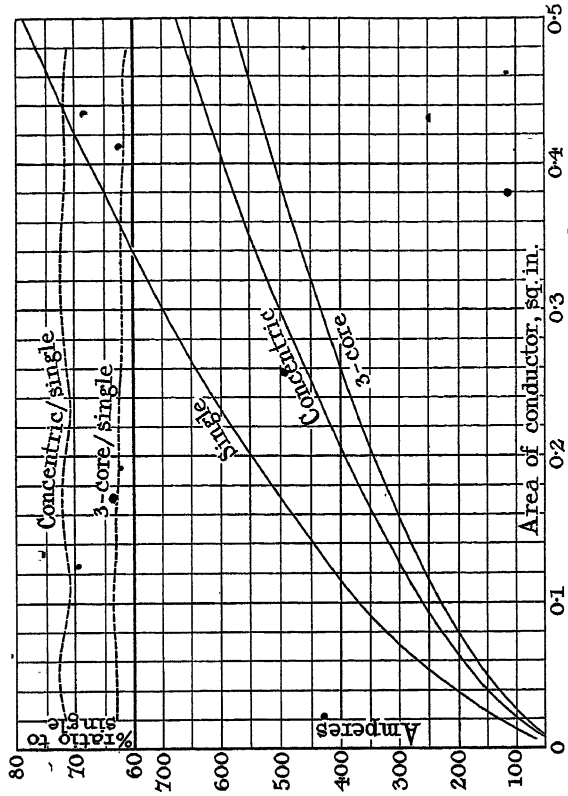

Fig. 47.—Comparison of 660-volt cables, single, concentric and 3-core armoured and buried direct (not earthed), $g = 120$.

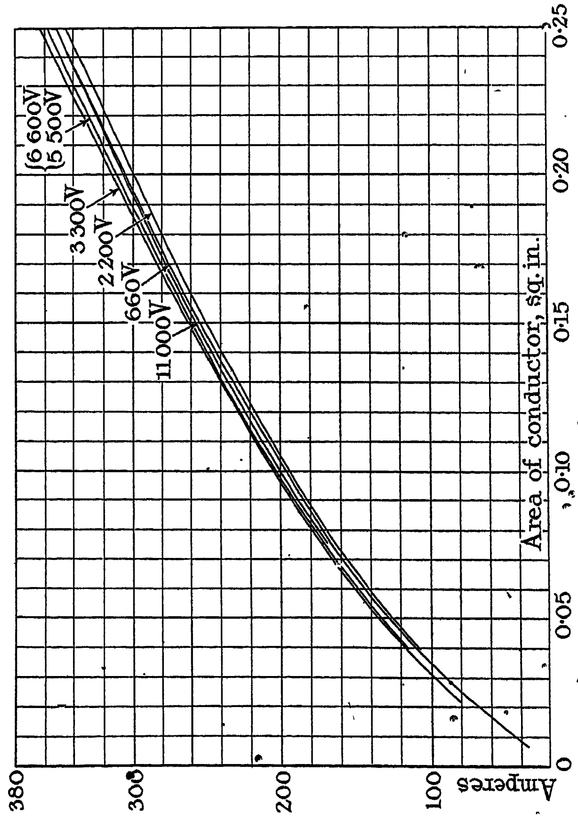

Fig. 48.—Concentric armoured cables in air, at various voltages.

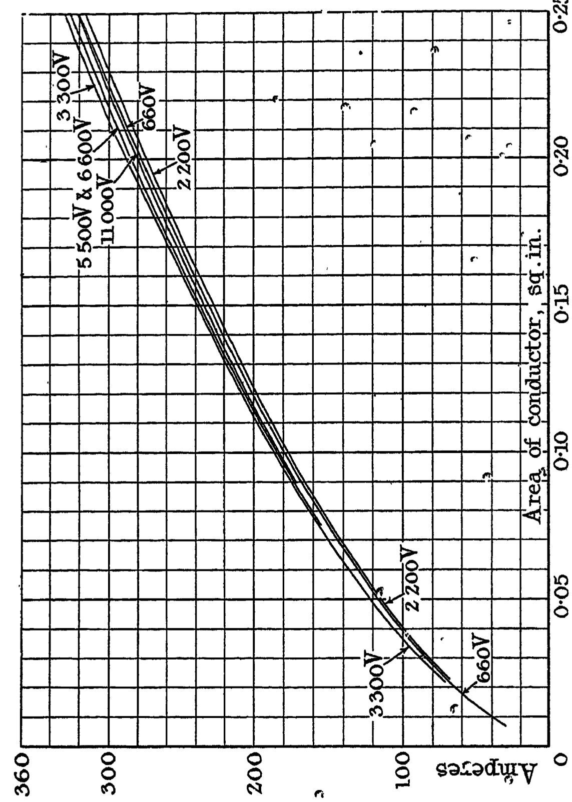

Fig. 49.—3-core armoured cables in air, at various voltages.

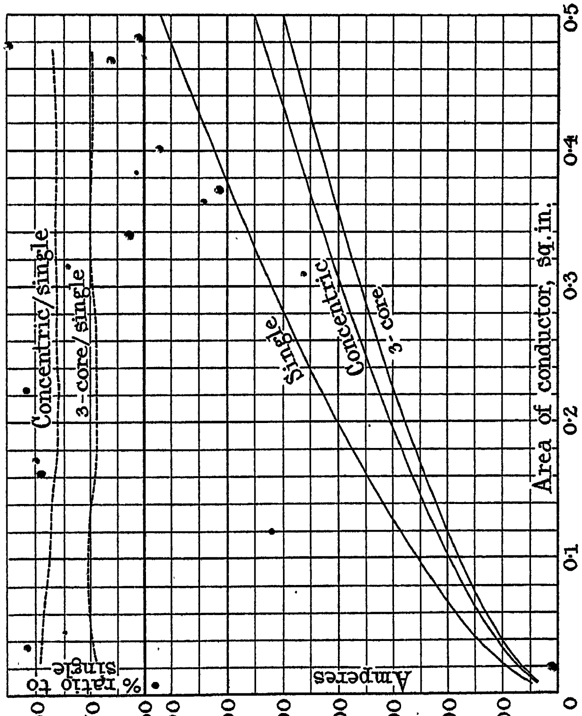

FIG. 50.—Comparison of 660-volt cables, single, concentric and 3-core in air.

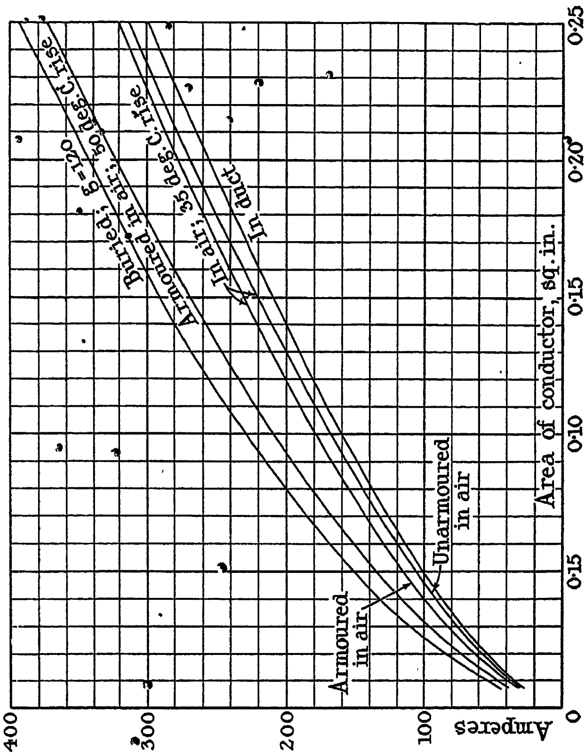

FIG. 51.—660-volt 3-core cables under different conditions of laying (not earthed).

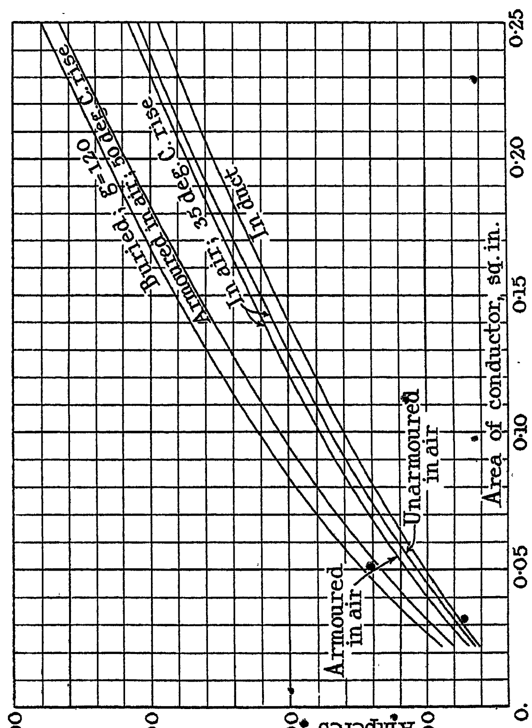

FIG. 52.—2 200-volt 3-core cables under different conditions of laying (not earthed).

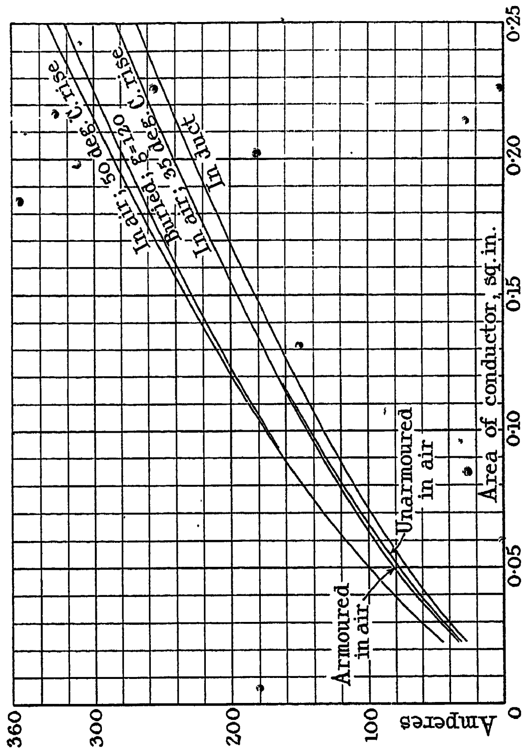

FIG. 53.—11 000-volt 3-core cables under different conditions of laying (not earthed).

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DISCUSSION BEFORE THE INSTITUTION, 1 MARCH, 1923.

Mr. Ll. B. Atkinson: The results of the research are presented to the Institution by the two authors, Mr. Melsom and Mr. Fawssett, in the form of a report to the Electrical Research Association, but as a matter of fact the great bulk of the experimental work has been done by these two members. In some ways I have been so closely connected with the growth of this report that perhaps it would not be reasonable and proper for me to make any criticisms now. I am therefore going to take this opportunity to say a few words on what appears to me to be a very urgent moral arising from this report. The great discoveries in electrical science, as in all other sciences, have in the main been made by single individuals. That will in all probability continue to be the case; that is to say, great minds concentrating their genius on some problem and reaching sometimes by logical processes, sometimes by intuition, and sometimes, we may almost be tempted to believe, by a transference of thought from outside, conclusions which they experimentally verify and which at one stroke seem to open up new worlds. That method of research by individuals will, I am quite sure, continue. But we must remember that it was an electrical man —Edison—who invented or discovered the process of a mass attack on problems by organized forces. I believe that the Menlo Park laboratory was the first instance in the history of the world of the realization of the definite belief that by putting a sufficient number of well-trained people on to almost any problem it could be solved, and that within a reasonable time. Earlier in the present week there took place the official opening of the General Electric Company's new research laboratories, an institution which already possesses a fine preliminary staff under the directorship of Mr. C. C. Paterson. That institution is an example of another form of research; that is to say, where a large concern deliberately establishes a department to solve its own problems and to make discoveries which it may use for its own benefit and its own profit, always realizing that necessarily, in the long run, the discoveries must profit others. In a smaller way, with less means and therefore at present more circumscribed as to its outlay, we have the Electrical Research Association, in the foundation of which this Institution was associated, where again the problem of research was approached from a different direction. Some researches there are which appeal and are of use to much wider groups of people than a single firm—which may, in fact, be of use to everybody in the electrical industry. It is the function of such a Research Association to undertake, at least as part of its work, the solution of problems which are of the widest application to every branch of the industry. A research such as the one with which we are now dealing is of no use unless it is published widely, and unless everybody in the electrical industry can and will make use of it. So far, however, although that is the case with this particular research, as it will be with others that the Electrical Research Association will develop, the burden of these researches is falling on a very few shoulders, and in some cases on the shoulders of those who are perhaps least interested in the matter. For instance, if, as I shall hope to show presently, the present report will result in some cases in less cable being required for a given service, it certainly appears somewhat curious that, apart from the contribution from the Department of Industrial Research, such a research should be paid for by the manufacturers of cables and not by the users. The manufacturers are, however, well aware that anything that can be done to cheapen the capital outlay on electric work is to their benefit in the long run, as well as to the benefit of everybody else. There is at times a feeling in some quarters that the Electrical Research Association has not so far produced any great results, or even results worthy of the expenditure and trouble taken. I think I shall be able to show that

that is a short-sighted view. The Association has, in fact, only existed for $2\frac{1}{2}$ years, and the present report is one of its first fruits. This report, within the limits to which it goes—that is the 11 000-volt cable—and including all the ordinary cables, puts us to-day for the first time in this position, that engineers or supply companies who have decided what cable will be used, and how deep it will be buried and, by a simple experiment, have determined how much moisture there is in the soil, and how many other cables are laid near it (all simple, easily-determined physical facts) are in the position, by the aid of this report, to say definitely what is a reasonable and proper loading (for a given temperature-rise) to put upon such a cable. Even if it be true that some cables are shown to be already overloaded, that is almost as great an advantage to the user as to find they are underloaded, because he is diminishing his future risk. At a conservative estimate, not less than £40 000 000 worth of underground cables are in use in this country alone for the purpose of distributing electricity. I think, also, it is no exaggeration to say that, with these tables before them, almost any supply undertaking may definitely improve the use of its cables by 10 per cent, either by diminishing the risk or increasing the loading, with perfectly definite knowledge. If that be a fair estimate, then the value in money of this report to the industry is something of the order of £3 000 000 to £4 000 000. If that be a correct way of looking at it, and if we say that cables are now being put down in this country at the rate of something like £2 000 000 to £3 000 000 worth a year, then, with the superior use of cables to be obtained as a result of this report, £200 000 to £300 000 a year will be gained by the industry. A certain group of manufacturers, belonging to two large Associations, has so far found all the sinews of war, except for a certain amount of very valuable help given now and in the earlier stages by this Institution. Now, however, we must press others to give financial assistance. The supply industry has not so far, perhaps, had an opportunity of doing so, but steps are being taken to remedy this and to enable them to join the Research Association as members. In saying this I must call attention to the great help given by the company with which Mr. Fawssett is connected, both in material support and in allowing its officials to devote much time to the work.

Dr. A. Russell: The authors discuss the heating of a three-core cable when only two of the cores are carrying current. On page 546 they show that the ratio of the thermal resistance between the three cores and the sheath to the thermal resistance between the two cores and the sheath is as 91 to 100, but the ratio of the electrostatic capacity between two cores and the sheath to the capacity between three cores and the sheath is approximately as 81 to 100. If the insulating material acts as a homogeneous medium to heat-flow, the two ratios ought to be the same. There must be a reason for the difference. When only two cores are loaded the sheath gets rid of less heat than when three cores are loaded. The sheath therefore is at a lower temperature and so also the insulating material is at a lower temperature. Hence, if the thermal resistivity increases as the temperature increases, this would explain the discrepancy. If the thermal resistivity has a temperature coefficient—just as the insulation resistance has a temperature coefficient—then the rating of cables for use in hot countries would be different from the rating in cool countries. The authors discuss the heating of conductors in air and call the amount of heat emitted per sq. cm of the surface of the cable per degree C. and per second the "emissivity constant." It is well known that this "constant" is greater for cables of small diameter than for large cables. It can be shown that it varies inversely as the square root of the diameter of the cable. An interesting experiment is described at the end of the report, where an experimental three-core cable is constructed and certain measurements are made to find out the error in the Russell formula when used at a part of the scale where it does not apply. The effect on the capacity of giving the cores a twist round the axis of the cable is measured. It is found that this twist—"lay," I think, is the proper term—has little effect on the capacity and therefore also on the thermal resistance. The reason of this is possibly that the twist increases the effective length and therefore the resistance of the core per unit length. There is consequently more heat to get rid off. At the same time also, whilst there is more metal per unit length there must be less heat-resisting material. These produce opposite effects and hence may produce a very small resultant effect. It is interesting to remember that the theory of the radial conduction of heat in cylinders which the authors have applied to everyday practical work was first given by Fourier in his *Théorie Analytique de la Chaleur* published over 100 years ago.

Mr. H. Brazil: I entirely agree with Mr. Atkinson's remarks on the very valuable work done by the Electrical Research Association, and think that the whole profession is deeply indebted to them. I cannot, however, agree with him that any engineer with this report before him will find it quite simple to determine, under any circumstances, what size of cable he requires to deal with a given load, and to what figure he must reduce the current on existing cables in order to be safe. On page 542 is given a table showing the permissible temperature-rise, and the figures vary from 25 deg. C. (German) to 50 deg. C. (British) and 85 deg. C. (Japanese), and I believe that the American figure approximates to the Japanese. Presumably cables are working at or near this highest figure, and it is therefore difficult to come to a decision as to which figure to use. Again, if cables are working at 85 deg. C. rise, it is very unlikely that an engineer working his cables at, say, 60 deg. rise would reduce the figure to 50 deg. in consequence of this report. Another difficulty that arises is the variation in the thermal resistivity of the soil through which the trunk main has to pass in getting from generating station to substation. In most cases the main will start in the country, and then penetrate through the outskirts right into the town or city. Those who have to lay mains in large towns will appreciate that all kinds of made-up soil have to be dealt with. In some cases there is scarcely any soil left, and the main has to be laid amongst pipes and ducts of various kinds. What value for the thermal

resistivity should, in the authors' opinion, be used in this case? If the main is of the same size throughout its whole length, this size must be governed by the thermal resistivity of the worst soil through which it has to pass or, alternatively, the size of the cable must be varied as the thermal resistivity of the soil varies, which is, I am afraid, an impossible proposition.

Professor E. W. Marchant: The great value of the report lies in the fact that it gives due weight to the very many variables that have to be considered, such as the character of the soil and the grouping of the cables, and it deals, of course, with high-pressure three-core cables. In common with Mr. Atkinson, I feel that the report will result in the saving of a great deal of money to supply undertakings. I propose to discuss one or two points in connection with the work that has been done. First of all, there is a difference shown for the permissible temperature-rise when a cable is laid direct in the ground and when it is laid in ducts; in one case it is 50 degrees C. and in the other 35 degrees C. The only reason given for this difference is the fact that there is greater liability to abrasion when the cable is laid in ducts. As stated in the report, the difference in permissible temperature-rise gives a difference of over 12 per cent in the carrying capacity of the cables, and tells very heavily, therefore, against the use of cable laid in ducts. Have the authors any definite information as to the abrasion of the lead sheathing of cables when they are laid in ducts? On page 537 it is stated that where current is passed through a cable there is an increase in the moisture surrounding the cable. It seems to me that this must be more or less accidental; I cannot imagine how the passage of current through a cable can tend to increase the moisture surrounding it. There is a reference in the report to the fact that the cable trough sometimes acts as a drain, and I think that is what must have happened in this instance. On page 543 it is stated, and I think quite rightly, that a cable route can sometimes be traced out by the drying of the ground above it. I should like to suggest the stream-line method used by Dr. Hele-Shaw which was shown before this Institution some years ago, for plotting out the stream-lines of heat-flow in a three-core cable. It was used in the first instance for tracing out lines of force, and was used here to show the lines of force from the armature tooth to the field magnet. It is stated in the report that the relative expansion of the core and the sheath is comparatively small. In one of the cases quoted, the actual increase in length of the conductor is about 1 inch, and the increase in length of the sheath is about $\frac{3}{4}$ inch. That means, of course, only $\frac{1}{4}$ inch relative motion of the core and the sheath, and the risk of trouble is therefore not great. I think the fact that the core tends to expand more than the sheath is important, and might not be expected, since the coefficient of expansion of lead is greater than that of copper. That, I think, has an important bearing on the use of aluminium cables. The coefficient of expansion of aluminium is about 50 per cent greater than that of copper, and therefore the liability to trouble from expansion is likely to be much more when aluminium is used than when copper is employed. It is stated in the report that the dielectric loss in cables is negligible at a pressure of 11 000 volts, and I think it is stated that the dielectric loss will increase rapidly when the temperature rises above a certain definite figure. Is not the dielectric loss due to temperature-rise caused by direct conductivity rather than by dielectric loss, as the term is ordinarily understood? The specific resistivity of a dielectric falls very rapidly indeed as the temperature rises, whereas I do not think that dielectric loss due to dielectric hysteresis alters to any appreciable extent with increase in temperature. I should be glad if the authors would give some definite information on that point. It would also be instructive to have some figures for the sheath losses in single-core cables carrying single-phase current. Suggestions for the use of such cables have been put forward within the past few months, and a good many figures of sheath losses have been published, but the information is not very complete.

Mr. T. N. Riley: The authors state on page 545 that the balanced-load condition is the least favourable from the point of view of temperature-rise. It is common practice to use cables for three-wire working in which the neutral wire is half the section of the two main cores. In this case it is not correct to state that the balanced-load condition is the least favourable. Let I and $(I - i)$ be the currents in the main cores (i being the current in the neutral core); R = resistance of each main core; $2R$ = resistance of neutral core. Then the heat developed is proportional to: $I^2R + (I - i)^2R + i^2(2R) = 2I^2R - iR(2I - 3i)$. In the balanced condition when $i = 0$ and again when $i = \frac{2}{3}I$ the heat developed is the same, and between these points the heat developed is reduced. If i exceeds $\frac{2}{3}I$ the heat developed increases and becomes a maximum when the current in one core is zero, when the heat developed is 50 per cent greater than in the balanced-load condition. It is unlikely in ordinary circumstances that the unbalanced load will ever be such as to make i greater than $\frac{2}{3}I$, and the case which the authors have taken will meet ordinary practice even if the third core is of half section. It is then difficult to see how a neutral core of equal section to the other two, as assumed by the authors, can be justified. Mr. Melsom stated in the discussion that the authors had not found any satisfactory method of plotting the lines of heat-flow. It appears to me that a similar method might be used to that described by Emanueli * in a paper dealing with the determination of the electrostatic field in a three-phase cable. It would at first sight seem quite possible to determine the lines of heat-flow for any cable under any system of loading. The cable would be represented by tubular conductors surrounded by a tubular lead sheath immersed in an electrolyte, and each conductor would be charged to a potential above the sheath proportional to the heat developed in it under the assumed load conditions. Emanueli used water as his electrolyte. The use of alternating current avoids polarization effects, and an electrodynamometer is used to give a "null method" detector and avoid disturbance of the field. The connections for exploring the thermal field are shown approximately

* *L'Elettrotecnica*, 1921, vol. 8, p. 573.

in Fig. A. Emanueli's experimental arrangements are fully described in the paper referred to. One advantage of this method is that it would enable sector-shaped cores to be dealt with in a manner impracticable by calculation, and it would afford a valuable check on Mr. Wedmore's graphical method in Appendix 4, which does not appear at all easy to apply with accuracy to sector-shaped conductors. The method would not, of course, allow for any difference in heat conductivity of the worming and the main core insulation due to difference of material or tightness of packing. It would be interesting to know whether the authors found this to be appreciable. I use "worming" here in the sense of the material employed to fill the interspaces between cores. There is an alternative method which seems to me to be feasible. If in any cable the dimensions were magnified to any extent, keeping the proportions the same, the thermal field would be similar. A model could therefore be constructed sufficiently large to use the thermo-couple method already employed for investigating the heat-flow in the ground outside the cable (see page 543 of the report). The actual material used as filling would only affect the magnitude of the thermal resistance and not the lines of heat-flow. The

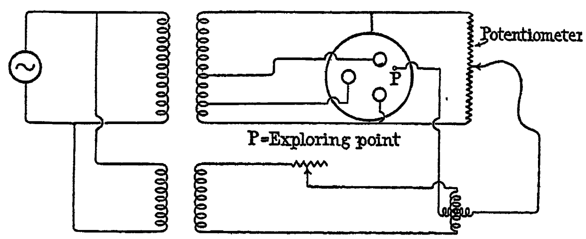


FIG. A.

effect of the worming might then be studied by using two materials of different thermal resistivity for the portions of the dielectric representing core or belt insulation and worming. If the thermal field is determined, a correction for filling material and absolute dimensions could then be very simply applied. The authors showed figures giving a comparison of the current loading of British and German cables. If we take the 11 000-volt case, the German standard thickness of dielectric is only 0·24 in. as against 0·3 in. in the British case, and for cables laid direct in the ground that would give a better cooling effect to the German cables and enable them to run at a higher current loading. In the opinion of the authors, is the difference in insulation thickness sufficient to account for the increased rating of the German cables?

Mr. P. Dunsheath: When the Preliminary Report appeared two years ago, some of us were disappointed because the contents were not such as could be applied to everyday problems of current rating, and we suggested that a simpler treatment based more closely on the thermal Ohm's law would be helpful. I am glad to find that, either because of the suggestions then made or for some other reason, the thermal-resistance treatment has been entirely adopted, with eminently satisfactory results. On page 535 two values have been adopted for thermal resistivity, one of 750 and the other of 550, the former for pressures up to and including 2 200 volts and the latter for pressures between 2 200 and 11 000 volts. Reasons are given for this classification, but they are not very convincing. On the same page the following statement occurs: "In view of the cost of manufacture it was considered unreasonable to expect that the lower-pressure cables would normally have a value of thermal resistivity as low as that of the higher-pressure cables." I should be glad if the authors could give a little more information on this point. I submit that, taking the whole of this and the previous report, the evidence is insufficient to warrant the adoption of those two values and that particular classification. Considering manufacturing operations, we should expect the values to be in the opposite direction. I think that the point should be verified very carefully before this is put forward as the last word. The footnote on the same page states: "Higher values have been adopted for cables with conductors having a sectional area less than 0·06 sq. in. to allow for the difficulties in manufacturing small cables." What is the reason for that statement? On page 538 the question of the thermal resistance of the soil is referred to. On later pages, and in particular page 544, the problem is worked out in detail. This, of course, is one of the difficulties of the whole investigation into the rating of buried cables. The method adopted in the report seems to be to make the assumption that the isothermal line coincides with the surface of the ground, and then to modify it by an arbitrary constant in order to make that assumption agree with the figures obtained, knowing at the same time that the assumption must be wrong. It is stated later in the report that the surface of the ground on a damp day dries over the cable, but not to any extent on either side. It does not seem right to assume that Kennelly's formula is correct and then add an arbitrary constant to make it fit the results. The real reason for the discrepancy seems to be that there is a temperature gradient in the ground before the cable carries any current at all, as is shown by some of these curves. In the summer, the surface of the ground is considerably hotter than the ground at a depth of two or three feet, and in the winter the gradient is reversed. Formula (26) shows that the deeper the cable is buried the greater will be the thermal resistance of the soil, and consequently the greater will be the temperature-rise. As a matter of fact, a cable buried deeper in the summer is put into a cooler spot, and therefore the reverse may hold; that is to say, the greater the depth the lower may be the temperature-rise. On page 541 another fundamental on which the whole of Table 31 hinges is that of the maximum temperature adopted. The figures are given as 65° C. for cables laid direct, and 50° C. for those in ducts. I think that the reasons for adopting the first-named figure are very good indeed. A previous speaker said that the Japanese were adopting higher maximum temperatures. The Americans also are doing so, but a report published three months ago in America showed the number of faults they allowed per mile of cable. The figure was ridiculously high from a British standpoint, so the fact that other nations are adopting higher temperatures is no justification for

our adopting higher figures than those mentioned in the present report. The arguments put forward for the maximum temperature of 65° C. are very strong indeed, but I am not so sure about those advanced to support the figure of 50° C. for cables in ducts. In American practice, where ducts are more common, the temperatures are very much higher than that, and I hardly think that the abrasion trouble referred to is a sufficient reason for having two maximum temperatures for the same dielectric. The paragraph on page 541 commencing: "The actual difference in permissible current-loading . . .," should, I think, read: "The actual difference in permissible current-loading between rises of 50 degrees C. and 35 degrees C., corresponding to final temperatures of 65° C. and 50° C. respectively . . ." In formula (49) * L should be in the denominator and not in the numerator, because the thermal resistance goes down with the length. On page 553 the time to attain the maximum temperature is dealt with. Not many people seem to realize that if a cable is buried in the centre of an infinite medium and quite a small current is passed through it, the temperature will rise indefinitely. This would not, of course, occur in practice, but I think that that phenomenon throws much light on the practical problem. I think that the sub-title "Effect of 'worming' on the capacity of the electrostatic model" on page 567 is incorrect. What is intended here is "lay," not "worming," and I suggest that the correct technical term be adopted.† In conclusion, I should like to emphasize an important feature of the report. For a long time a need has been felt for a set of current-carrying tables which could be accepted as standards, but it was important that they should be published in such a way as to command confidence. The authors must have been tempted at times to dwell on more academic points, but they have gone, I think wisely, straight to the practical problem, and so have produced a precise authoritative statement which will command the respect of engineers which it deserves.

Mr. E. B. Wedmore: Mr. Atkinson has already dealt admirably with this report from the point of view of the Electrical Research Association, but I should like to add a few remarks. Members are aware that the Association has in hand other researches which affect the whole industry. I suppose it is true to say that the whole of the work of the Association is and will be of value to the whole of the industry. We have researches now in hand, however, which are of particular value to those engaged in power supply. We are conducting researches which will add to the economical use of overhead line material, researches on the construction of poles, which will undoubtedly lead to a change in the design of poles designed for carrying overhead lines, and researches on switchgear, amongst others in this category. Mr. Atkinson has referred to £200 000 to £300 000 a year as the saving likely to accrue to the industry as a result of this report alone. I feel that the Association can reasonably seek to secure at least 10 per cent of this sum. There is a particular claim which I should like to put forward at this stage to those members who are connected with electric supply. Manufacturers are not yet free of the financial difficulties through which the whole industry has been passing of recent years. Business is turning the corner, but only slowly. On the other hand, I think it is a fact that power supply companies have well turned the corner. Undoubtedly the municipal supply authorities also, who will benefit by these tables, are in a happier position financially than they were a few years ago. This is a favourable time, therefore, for supply undertakings to consider their indebtedness to the Association and to consider the possibility of co-operating in the work now being done, work from which they will so obviously derive benefit. It has been briefly indicated that the Association has in preparation a scheme of Associate Membership for bringing these people more closely in touch with us. We desire their co-operation in every way. The whole effort of the Association is co-operative, not only in its financial aspects, but in every direction; we want the whole-hearted co-operation of everyone who is interested in research as a means of advancing the industry. It is hoped to distribute particulars of this scheme of Associate Membership to all those interested, and we hope that power companies, municipal authorities and large users will see their way to appoint representatives to co-operate with the Association in the capacity of Associate Members, and help to finance our researches by substantial subscriptions. We have already had promises recently of £250 to £500 from each of several large corporations engaged in power supply, towards particular researches.

Mr. P. V. Hunter: I should like specially to draw the attention of engineers to those tables in the report which show the permissible loading which may be adopted in the case of cables laid together. In the past there has been a fairly general knowledge on the question of the actual heating of the ordinary types of cables when laid according to the methods in general use, but there has been no reliable information available as to the effect of the mutual heating of cables in the same trench. The information given in Table 37 of the constant to be applied when cables are laid at different spacings in the same trench is therefore, I think, of very great value indeed, and is hardly given sufficient prominence in the report. Have the authors any information for rather larger separations than the 12 in. given? In many cases it is customary to space the cables rather farther apart, up to 18 in. or even 2 ft. There is also the question of the cause of temperature-rise in cables laid direct in the ground. Various mathematicians have visualized it in different ways, and I gather that the authors could find no test-results which agree with the mathematical formulæ. It seems to me that the assumption that all the lines of heat-flow eventually reach the surface of the ground must be right. In practice the energy must be dissipated in the atmosphere. The weakness in that particular mathematical formula seems to lie in the assumption that the surface of the ground is also an isotherm. If a cable were buried at such a depth that the lengths of the lines of heat-flow from the cable to the surface were all approximately equal, the surface of the ground would approximate to an isotherm. For this condition

* Corrected for the *Journal*.
† This suggestion has been carried out.

to hold, however, the depth must be very great as compared with the diameter of the cable: probably many times greater than is the case in ordinary practice. For this reason it is necessary to make a rather large correction to the formula—as much as $33\frac{1}{3}$ per cent, I understand.

(*Communicated*): There is one other matter which appears to require some further consideration, namely the permissible current loading of cables in air. On page 522 it is stated that for cables in air and drawn into ducts the temperature-rise allowed is 35 deg. C., the maximum permissible temperature being 50° C., from which it is deduced that the atmospheric temperature is 15° C. In the case of railway companies it is common practice to suspend high-tension cables in air and exposed to direct sunlight, and it seems to me that at certain times of the year the atmospheric temperature must substantially exceed 15° C. I should expect it at times to reach 40° C. Assuming for the moment the same temperature-rise, namely 35 deg. C., this would give a total temperature of 75° C., which seems likely to be the condition which would result if cables suspended in this way were loaded in accordance with Tables 16 to 21. It is probable that for these particular conditions the limit of maximum temperature of 50° C. need not be adhered to, as this is primarily a limit set in connection with cables drawn into ducts. For cables laid underground the limit is 65° C., which is still 10 deg. less than the 75° C. mentioned above. A particular cable carries its maximum load only occasionally, i.e. when circumstance requires some of the cables to be out of service at the time of maximum load. For a temperature of 75° C. to be reached these cables have to be out of service not only at the time of maximum load but also during that brief period of the year when the atmospheric temperature is highest. For this reason, therefore, the probability of any particular cable attaining to the temperature of 75° C. is small, and it is doubtful if any harm would accrue from such a temperature if it occurred for only a few hours in the course of several years, provided the cables are for working pressures not exceeding 11 000 volts, where the increment of dielectric loss with temperature is not a material factor. On the whole, therefore, the conditions are probably not so alarming in practice as they would appear to be on paper, but in view of the imminence of schemes of railway electrification and of the tendency for the advisers of railway companies to adopt this mode of erection for cables, it would probably be of value to the industry if the Committee would give it some more special consideration than has been done in the report. The capital expenditure involved is several millions of pounds eventually, and the railway companies might therefore be asked to contribute a little money for a special series of tests, the results of which could be embodied in a small supplementary report.

Mr. P. Rosling: I think that the wrong terminology * is used in regard to the concentric cables, where columns are headed "Centre Point Not Earthed" and "Centre Point Earthed." Concentric cables may be used for single-phase transmission, and I think that the headings should be "Outer Conductor Not Earthed" and "Outer Conductor Earthed." I take it that the loadings given are safe loadings for these cables in certain circumstances; it does not by any means follow that they are the loadings which it will pay best to put on the cables. They may be satisfactory for temporary running, but an examination of the losses entailed by these loadings will show that to-day, with the high price of coal and low price of copper, such loadings will not be economical in usual practice.

* Corrected for the *Journal*.

Mr. E. T. Williams: There is one small point which has not been referred to in the report, namely the emergency loading of cables for a short time. All power engineers know that when laying down networks it is desirable to look to the emergency and to consider how the supply can be kept going in the event of one cable breaking down, and to what extent cables can be over-run without permanent injury, or even any injury at all. Information on that aspect of the work would be of very great value to engineers engaged in designing lay-outs. In common with Mr. Atkinson and Mr. Wedmore, I feel very strongly that not only financial support but sympathetic support should be given to those who are trying to advance this cause of research. In my official position I have come very intimately into contact with not only the value of this research in experimental work but also the great difficulties that have to be contended with.

Mr. W. A. Del Mar (*communicated*): The source of this report, the names of the authors and of the Committee members, lend great authority to its recommendations and ensure its usefulness to British cable users. It may be of interest, however, to consider how this report would be received if presented to an American audience. In this case the emphasis would have to be put on the use of cables in ducts, this being the almost universal practice in America. The Standards of the American Institute of Electrical Engineers allow the insulation at the surface of the conductor to attain a temperature of 85° C. less 1 degree C. per kilovolt working tension in the circuit. Thus a cable for 11 000 volts may be operated at a temperature of 85 − 11 = 74° C. This formula is an empirical one approximating a rational one based upon the assumption that cables must not be allowed to carry a greater load than a certain percentage of that load which would give cumulative heating with insulation of the power factors obtaining when the rule was formulated. Practical operating experience was also drawn upon in arriving at the final formula. This rule had served for about 8 years when the general reduction of dielectric losses and the rise in commercial tensions led to its re-appraisal by a committee of the Institute. It was pointed out that while the rule gave satisfactory results up to about 25 000 volts, it gave temperatures which were obviously too low for the new 33 000- and 44 000-volt cables. The manufacturers of these cables were willing to guarantee them for continuous operation at 60° C., whereas the rule gave 52° C. and 41° C. for 33 000- and 44 000-volt cables respectively. The Institute, however, was not in possession of sufficient experi-

mental data to make an adequate revision of the rule and it was therefore decided to hold a meeting devoted to a symposium on the failure of insulation under stress, and to make this the starting point of an exhaustive research. The symposium was held at Niagara Falls, Ontario, in June 1922 and the research work was started at about the same time, under the direction of Professor Bush, of the Massachusetts Institute of Technology. This work is financed by the National Electric Light Association, which is an organization of central station companies, and is under the control of a joint committee of that Association and the American Institute of Electrical Engineers. In 1921 the basic figure of the American rule, 85° C., was discussed in a symposium on the heating of low-voltage cables. This symposium is quoted in the report under discussion, and it is incorrectly stated that the temperature-limits for impregnated paper cables proposed by American engineers in 1921 were "all based on consideration of the mechanical properties of the paper only." As one of the authors and as chairman of the committee under whose auspices the papers were presented, I can say with authority that the authors took into consideration all operating features of which they knew affecting low-tension cables, i.e. cables in which neither dielectric stresses nor dielectric losses have any perceptible influence. In particular, the subject of thermal expansion was fully considered. It seems to me that the authors of the report beg the question at issue when they say that "after full consideration of all the various factors involved, it was decided to adopt 65° C. for the maximum temperature of the conductor for armoured cables up to and including 11 000 volts working pressure laid direct in the ground," and "in view of the fact that a cable drawn into a duct is free to move lengthways along the duct and cause injury to the lead by abrasion, it was considered that the permissible temperature should be lower than that for cables laid direct in the ground. It was decided, therefore, to adopt 50° C. for the maximum temperature of the conductor, etc." When hundreds of miles of cable are operating successfully at temperatures from 24 to 35 degrees C. higher than the 50° C. adopted, the exact reasons for adopting the latter figure should be stated. The statement that it was adopted after "full consideration of all the factors involved" is rather like the embarrassing moment at a mathematics lecture when the professor says "it is obvious that" and then the whole thread of the discourse is lost. It would seem that the major part of the research should have been directed toward ascertaining and giving full reasons for the temperatures adopted. This is the course which, as explained above, has been adopted by the Cable Research Committee of the National Electric Light Association and American Institute of Electrical Engineers. The importance of the maximum allowable temperature may be seen at a glance if the ambient temperature of a duct line be assumed to be 30° C., as the permissible rise for an 11 000-volt cable would be 44 degrees in American practice and 20 degrees in British practice. An assumption of 15° C. duct-line ambient temperature is difficult to understand, especially in view of the reduction factors to be used in calculating the carrying capacity when several cables are present. The relative carrying capacities of a cable under the American and British rules would then be in the ratio of $\sqrt{(44)} : \sqrt{(20)} = 1\frac{1}{2}$ approximately. It is hard for an American to understand why British cables should be loaded to only two-thirds of the current that American cables normally carry. There also seems to be a confusion of thought where Kelvin's law is cited as a limiting factor. This law does not give 50° C. as the economical temperature regardless of the cost of labour, coal and copper. The maximum permissible temperature should not be confused with the most economical temperature from the point of view of copper losses. The work on Mie's formula is very thorough and useful and will be greatly appreciated by American cable engineers.

Mr. A. Rosen (*communicated*): Dr. Russell has suggested that the thermal resistivity of the dielectric might vary with the temperature. This possibility occurred to me some little time ago, and the following

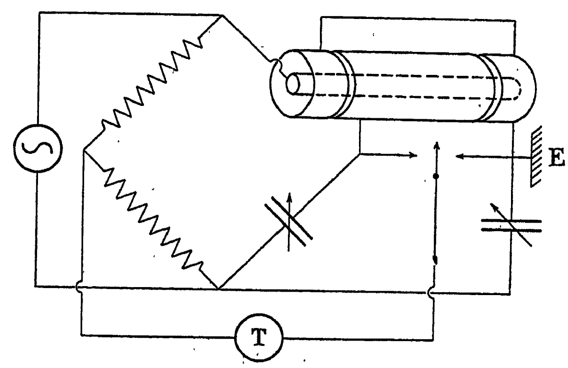


FIG. B.

experiment was carried out to investigate the matter: A 220-yard length of three-core 0·15 sq. in. 22 000-volt cable, coiled on a wooden drum, was immersed in a comparatively large volume of water, and sufficient current was passed through the three cores in series to give a temperature-rise of about 20 deg. F. above the water. When steady conditions were reached the heating current was switched off and the fall of resistance with time was measured on a Kelvin low-resistance bridge, so that it was easy to deduce the exact resistance and thus the temperature of the cores at the moment of switching off. The test was carried out with the water at 60° F., 100° F., 140° F. and 175° F., the other conditions remaining the same, so that the results should be strictly comparable. It was found that the thermal resistance decreased with temperature in a regular manner, the ratio of the resistivities at mean temperatures of 69° F. and 183½° F. being 1·62. It was intended to carry out further tests to confirm this interesting result, but the pressure of other work has so far prevented this. In regard to the discrepancy between the electrostatic analogy and the thermal case when the loading on a three-core cable is eccentric, as described on page 546, one would like to know the

temperatures of the cores and sheath. If the mean temperature of the dielectric were different in the two cases, the change in the thermal resistivity might account for the 10 per cent difference. There are two other factors worthy of consideration: (1) If the "worming," i.e. the material used for filling the spaces between the cores, was of jute, its thermal resistivity may have been different from that of the paper, and so the dielectric would not be homogeneous; and (2) the electrostatic analogy demands that the cores and sheath should be perfect conductors as compared with the dielectric. Taking the figures on page 534, the thermal resistivities of impregnated paper and lead are 500 and 2·9 respectively, giving a ratio of 172 : 1, and this is of a much lower order than in the electrical case. Thus, when the two cores were used for heating there would be a difference of temperature in the sheath, i.e. the surface of the sheath and possibly that of the idle core would no longer be isothermals. Both (1) and (2) would modify the distribution of the lines of heat-flow and so affect the comparison with the capacity tests. In Appendix III, in describing the electrostatic model, the trouble caused by end-effects is referred to. This can be overcome by providing the outer cylinder with guard-rings at either end, and using the Wagner double bridge * to measure the true capacity. The circuit is illustrated in Fig. B.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 12 MARCH, 1923.

Mr. P. T. Allan: The expression of the principal quantities in electrical measure, thus avoiding the use of conversion factors, is a particularly useful feature of the report. Criticism must be confined to the few errors of statement which are bound to creep into a work of such magnitude, and perhaps to one or two of the assumptions made. In general, I find myself in agreement, so far as my own experience and knowledge go, with most of these assumptions. It must be realized, however, that to make these figures of permanent value cable makers will need to be asked to guarantee the thermal resistance of their cables or the thermal resistivity of the insulating materials employed. This may have the effect of shutting out some foreign competition of a harmful nature. Also, it must not be forgotten that the high current-carrying capacities of many of the lower pressure cables cannot always be taken advantage of except for short lengths. While I realize that the Committee and the authors, in limiting the maximum temperature to 50° C. for cables laid in ducts, were guided by a mass of information not available to myself and other individuals, I do not think that they have quite made out their case for this particular assumption or decision. Mr. Fawssett in presenting the report mentioned that the 35 deg. C. rise applied to cables both in air and in ducts. It is not made clear in the report whether or not it is intended that the final temperature in air should be 65° C. or not. I am particularly interested in the air figures on account of their possible application to mining conditions, as they will form a useful basis for further investigation of the peculiar conditions applying in mining work underground. One effect of a report such as this will be to remove the excuse that there are no definite figures to go upon, and therefore to throw greater responsibility on engineers engaged in the design of distributing systems. They will be required to make proper allowance for all the varying conditions met with. On pages 519 and 538 the authors say that a large amount of data has been collected in respect of various countries, including India and Australia. They further state that "the Australian figures are not greatly higher than these," referring to British figures just quoted. I feel that these statements are really misleading, omitting as they do any reference to the moisture content and the other characteristics of the soil, and particularly in that they represent very small and (in the case of Sydney, Perth, Adelaide, and Calcutta) not very typical parts of the countries mentioned. It may be agreed that a very large proportion of the electrical development in these countries is centred in a few large cities, but due qualification should be made in the report in its final form, or otherwise mistaken assumptions may be made. I do not at all like the idea of obtaining information about these large and important countries through a single source, and that only an indirect one. It would have been much more gratifying to our fellow engineers in responsible positions abroad, many of whom feel that they are cut off from the activities of the parent Institution, if the Committee had asked the various Local Hon. Secretaries to send out a proper questionnaire to all the members resident in their territory, and I feel certain that the resulting information would have added materially to the value of the report. I am interested in the explanations given of the reasons for error in Russell's formula, and the limitations of its practical application. Will the authors be good enough to give a similar statement with regard to the reason of the error between the theoretical calculations of the value of g and the actual experimental results obtained?

Mr. C. Turnbull: With low-pressure current we cannot usually run cables at a density which will cause them to heat unduly, as the drop of pressure becomes too great before that, but with extra-high pressure a different state of things takes place. Modern superstations require a pressure of 20 000 to 30 000 volts to enable them to transmit the current in cables of practical size. A 10 per cent pressure-drop, or more, is common enough with low-pressure supply, but a drop of 2 000 or 3 000 volts on a high-pressure cable would usually involve an impossible current density. This means that Kelvin's law does not apply to these, but that a strict watch must be kept on temperature: it will in fact be as necessary to study the heating of underground

* K. W. WAGNER: *E.T.Z.*, 1911, vol. 40, p. 1001; also S. BUTTERWORTH: *Proceedings of the Physical Society*, 1921, vol. 34, p. 8.

cables as that of conductors on generators and transformers. This brings us to the difficulty that soil conditions are not only difficult to predict but that they may vary by the running of other mains in the neighbourhood, mains which in some cases may belong to another authority. Where mains are to be run at the highest densities, it will be necessary to increase their section in places congested with a large number of other mains, e.g. where they enter the station or substations. I would suggest that the curves might in some cases be simplified by the use of logarithmic ruling.

Mr. J. Y. Hutchinson (*communicated*): A satisfactory theoretical treatment of the heating of buried cables is very difficult and must involve some empirical matter, but it seems to me that a more straightforward consideration of the subject might be found than the one presented in the report. To my mind the whole question centres round the correct application of the fundamental formula $H = t_1/(S + G)$ in which $(S + G)$ should be the thermal resistance between two isothermals in the heat circuit and t_1 the difference in temperature between the *same* two isothermals. One of the isothermals will be the surface of the conductor and the other may be any isothermal within the ground. The values of G and t_1 will vary according to the isothermal chosen, but for any value of G there will be a corresponding value of t_1, referring to the same isothermal. Any value of G will be useless for substitution in the formula without definite knowledge of the corresponding value of t_1. If t_1 be taken as the temperature-rise of the cable, then G should be the thermal resistance of the heat circuit between the outer surface of the cable and the isothermal corresponding to the original temperature of the cable. This latter isothermal may be in the ground or, more likely, will cut the surface of the ground and be in the air. In this case part of the heat circuit will be in air, and G must include the equivalent of the thermal resistance of the air. On the other hand, if G refers simply to the thermal resistance of the ground then t_1 should be considerably lower than the rise in temperature of the cable, since the temperature even at the surface of the ground will be considerably higher than the initial temperature of the cable if isothermals cut the ground. It seems to me that the best treatment would be to ignore Kennelly's formula and to obtain a new empirical expression for the thermal resistance of the heat circuit between the outer surface of the cable and the isothermal corresponding to the initial temperature of the cable. If, when comparing practical results with theoretical results, t_1 were taken as the rise in temperature of the cable, then it would seem from the above that Kennelly's formula is more inaccurate than a 0·6 correction factor implies. The investigation of the distribution of isothermals, as described, is not altogether satisfactory, owing to the comparatively small size of the box and the use of a medium of high resistivity which results in isothermals entering the air on all four sides. The fact that the cable was vertical also affects the result to some extent, as the heat at the surface will not be so effectively dissipated by convection as in the case of a horizontal cable. The results of further investigation under varying conditions of depth and resistivity would be interesting.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

North Midland Centre, at Leeds, 20 March, 1923.

Mr. W. E. French: I wish to confine my remarks to one or two points which seem to have an important bearing on the maximum carrying capacity of cables buried in the soil. When studying the Tables 3 to 14 for cables buried directly in the soil (and also the curves shown on the screen) one is immediately confronted with the great importance of the soil resistivity, g. According to these tables and curves the maximum current-carrying capacities of cables may be increased by 25 and even 50 per cent, the increase depending entirely on the resistivity of the soil surrounding the cables. A study of the curves giving g as a function of the moisture of the soil and the quality of the soil, shows that g may vary between 90 and 340 to 400, these figures also being quoted in Table 31 as the proposed British Standards or, rather, as the basis on which the British Standard cable loading will be based. On the other hand, some Continental writers on the subject quote 50 as a good average value for the soil resistivity. Therefore, the maximum current-carrying capacity of a cable is largely determined by g, which in turn depends on the nature and moisture of the soil in which the cables may be buried. I think that this rather represents one of the troubles which may be experienced in the use of the tables mentioned. The engineer responsible for the design of the network naturally desires to work his cables at their best current-carrying capacities and he must therefore have the fullest information regarding the resistivity of the soil through which his cables will pass. The method adopted for the determination of g, while perfectly valid in itself, appears to me rather to give confined laboratory results than to furnish figures more in accordance with the actual local conditions of the soil in which the cables are laid. The guard-ring method rather limits the information on g to a few samples of soil. I have in mind an alternative method which was first proposed by Ångström, and later modified by Forbes and Kelvin for the determination of the thermal conductivity of the earth's crust; it is the method of periodic heating and cooling and can be made directly applicable to the determination of the thermal conductivities or resistivities. During the day the earth's surface is heated, and during the night is cooled; therefore a series of heat waves pass from the earth's surface to the interior. If the heat wave-length and its periodic time are known, the diffusivity (according to Kelvin the ratio of the thermal conductivity to the thermal capacity per unit volume) can be calculated, and from this the conductivities and resistivities could be deduced. If the periodic variations are uniform, and assuming that in any locality the soil may be considered to be reasonably

uniform, then the heat-waves passing through the soil may be taken to be the same as with a bar periodically heated and cooled. Thermometers or thermo-couples buried at various depths would record the progress of the diurnal heat-waves; the wave-lengths could be determined and, assuming a simple harmonic function of the temperature, the diffusivity could be calculated for the expression $K = \lambda^2/(4\pi T)$, where λ = wave-length, and T = periodic time of the heat-waves, and from this the resistivity could be found. This method if standardized would lead to a far more universal investigation of g, and even provide the engineer with a means of conducting his own thermal survey of the soil through which his cables have to pass. When discussing the first report I pointed out the desirability of investigating the heating of cables with regard to the thermal time-constants, and so establishing data and a method by which the thermal characteristics of a cable could be predicted. I understand that the authors have gone into this question, and that they are reserving this question for a separate publication. I should therefore prefer to reserve any remarks which I may have to make on this point until I have had an opportunity of reading this further paper.

Mr. J. W. J. Townley: One of the difficulties which I foresee in the use of the tables is the determination of the value of g, the thermal resistivity of the soil. In this district, with a fairly heavy clay soil, I think that the value of g might be safely taken at 180, and it would be very desirable indeed if a table could be prepared giving an average value for g for various districts throughout the United Kingdom. This work might well be undertaken by the Local Centres, and could be published with the tables so that an engineer working in a strange district would find in them a safe average value of the thermal resistivity of the local soil. No doubt wide variations in the soil will occur on any particular route, but it will be necessary to determine average values for everyday practice, and it should be remembered that the maximum-current tables given in the report are based on relatively low temperature-rises, so that the factor of safety is high. Another point which has occurred to me is that where voltage-drop conditions will allow of cables being loaded to the maximum values given, in many cases network boxes, fuse pillars and other accessories will require to be replaced to take full advantage of the maximum load capacity of the cables which, on past standards, will be quite inadequate for the new ratings. Mr. Melsom has pointed out that armoured cables have a higher carrying capacity than similar cables unarmoured. Were the armoured cables he used of the usual form, in which the armouring is laid over jute or Hessian tapes and jute-served or Hessian-taped overall? It would appear that a marked difference would be effected in the radiating capacity of a cable by putting the armouring directly in contact with the lead, but the report does not distinguish between these two forms.

Mr. R. M. Longman: The subject of this report is of special interest to me, as it was my good fortune in 1905 and 1906 to assist Mr. Fawssett in the original tests carried out in this country, and it was at the completion of these tests that I noted the first reference to the work of the V.D.E. on the subject, as published in *Science Abstracts*. These tests were carried out on 6 000-volt cables and no attempt was made to take into account the effect of moisture in the soil,* but on plotting the figures obtained alongside the figures given in the paper a remarkable close agreement is shown with the figures for $g = 180$. I have little doubt that the figures thus obtained have largely formed the basis on which many engineers have worked for the past few years, with probably only a very slight idea of their origin. I cannot recollect any case of cables at this loading having suffered any deterioration or damage; I am aware of a 20 000 volt cable which had been run at much higher loading for long periods and which on the removal of a short length, not due to breakdown, showed signs of deterioration, the impregnating oil having become dry and patchy. This may be looked upon as the beginning of the end, as hot spots and puncturing of the layers of paper may occur which are no longer healed up by the action of the impregnating oil; even so, the cable will probably last for many years, particularly if not overloaded. Have the authors experienced any similar cases? With regard to the samples of soil tested, I believe these have been chiefly taken when laying new cables. Have samples also been taken along cable routes where the cables are heavily loaded? The tendency in such cases where a certain amount of heat is generated is to find the soil drier than is otherwise the case. Have any tests been made along a heavily loaded cable route to determine the isothermal lines by taking simultaneous temperatures of the soil immediately above the cable and a short distance, say 18 in. or 2 ft., on each side, the thermometers in each case being placed at equal depths in the soil, say 2 in.? Are the V.D.E. figures given in the report the same as those which appeared in *Science Abstracts* in 1905 or 1906? With reference to the bunching or grouping of cables such as is often necessary when leaving a power station or substation, a considerable gain in capacity may be obtained by the careful arrangement of the same by interspersing pilot or telephone cables or lightly loaded cables between those more heavily loaded. Attention to such a point may easily increase the capacity of the cables by 10 per cent. In some cases where excavation costs are high it may be advisable to provide more copper, the cost of excavation being balanced against the extra cost of cable. A type of laying to which the authors have not alluded and which has been extensively used, is the laying of cables in iron troughing which is then filled in with pitch or bitumen. Can they furnish information as to the permissible loading in such cases? Such cables are not armoured and this method of laying cannot be described as the "solid" system. Many such cables are arranged alongside a wall, for instance in tunnels, under bridges and in railway cuttings, and unfortunately in many cases they are fully exposed to the sun.

Mr. W. B. Woodhouse: The work that the Research Association has done in this matter is of very great value because it will help us to reduce the cost of distribution in a number of cases. In a paper which I read some little time ago, I pointed out that in the

* *Journal I.E.E.*, 1922, vol. 59, p. 85.

majority of cases the application of the economic law of minimum total annual cost of distribution showed that the economical current rarely reached the limiting value for the cable, but even so it is of value to know in every case the practical limit of loading. Users of cables have to consider in practice that their cables are laid in different soils and under different conditions, e.g. where they run in substations or pass through ducts. It is usually impracticable to cut the cable and introduce a short length of larger cable. Where the cooling effect is reduced in this way the possibility of introducing additional means of radiation is worth considering. For example, the trench might be packed with some material of high heat conductivity, the cable might be fitted with radiating fins, or water cooling might be adopted. There are many ways of dealing with this problem and our more accurate knowledge of the heating is of benefit. An accurate indication of the average temperature of a long length of cable is easy to obtain, but the important matter is to determine the maximum temperature at a hot spot. The research has brought out in an interesting way the relative cooling of cables laid at different depths. There has been a tendency to exaggerate the effect of laying cables in deeper trenches. The report shows a comparatively small difference for practical depths, and even this difference may be substantially modified by the additional percentage of moisture in the deeper trenches. The results should emphasize the fact that the grouping of cables in ducts is bad, not only on account of the reduced radiation, but also because of the smaller degree of safety in case of breakdown.

Mr. W. R. T. Skinner: I have compared the figures given by the authors with those in the I.E.E. Wiring Rules. The figures are not strictly comparable for all classes of cables and the I.E.E. tables were not intended for buried cables, but, in default of other loading tables, the I.E.E. Wiring Rules have formed a basis for cable ratings and consequently the comparison may be of some use. The comparison is best made by considering the values of the thermal resistivity of the ground to which the ratings given in the I.E.E. tables correspond. One finds that for 11 000-volt three-core 0·25 sq. in. cables the equivalent value of g is 230, increasing to 340 in the case of a 0·075 sq. in. cable. For cables smaller than 0·075 sq. in. the equivalent value of g is greater than 340. Again, for 2 200-volt three-core cables, one finds that for a 0·25 sq. in. cable the equivalent value of g is 280, increasing to approximately 340 for a 0·10 sq. in. cable. For sizes below 0·10 sq. in. the equivalent value of g is greater than 340. It is clear from these figures that, if the I.E.E. tables have been used for buried cables of the types considered, the loading has been well on the safe side for all but the worst conditions of the ground, from the point of view of thermal resistivity. With regard to the curves of maximum ground temperature, I should like to know whether it would not be an advantage to show the highest maximum temperatures occurring in the past 12 years, instead of the average maxima, or whether this curve is covered by the two curves for the exceptional years 1911 and 1921. I notice that the difference between the current-ratings for cables used on systems with an earthed centre point and those used on systems with an unearthed centre point, is only some 4 per cent at the most. In view of the fact that some speakers have already mentioned the possibility of simplifying the tables, if that difference of 4 per cent is not justified by the assumptions on which the tables are based, could not the two sets of tables be merged into one?

Mr. H. P. Bramwell (*communicated*): Since the publication of the Preliminary Report, I have carried out a number of tests of the moisture content of the soil in the Bradford district. The results are given above, tabulated in a form comparable with those for

Nature of Soils	Nature of Surface	State of Surface	Date taken	Depth taken	Moisture
					Per cent
Yellow clay, much sandstone ..	Flags	Damp	22/11/21	3 ft. 0 in.	13·7
Stiff clay	Square sets	Damp	22/11/21	4 ft. 0 in.	13·5
Shale and soft rock	Flags	Damp	1/12/21	1 ft. 6 in.	13·5
Stiff clay	Flags	Damp	1/12/21	1 ft. 6 in.	12·4
Clay	Unmade	Wet	1/12/21	1 ft. 6 in.	25·0
Sandy soil and sandstone ..	Flags	Damp	1/12/21	3 ft. 0 in.	10·4
Sand and clay in thin layers ..	Flags	Damp	23/2/22	5 ft. 0 in.	18·4
Clay	Flags	Damp	8/12/22	4 ft. 0 in.	13·2
Sandy soil and sandstone ..	Flags	Damp	8/12/22	2 ft. 3 in.	9·7
Soil, ashes and cinders	Tarmac	Damp	23/2/23	2 ft. 3 in.	15·0
Soil, ashes and cinders	Ashes	Damp	23/2/23	1 ft. 9 in.	30·0
Clay and sandstone	Flags	Damp	23/2/23	1 ft. 6 in.	14·6
Stiff dark clay	Unmade	Wet	3/3/23	1 ft. 8 in.	14·5
Clay with cinders and shale ..	Flags	Dry	13/3/23	2 ft. 6 in.	21·5
Dark clay and soil	Square sets	Dry	13/3/23	4 ft. 6 in.	19·6
Dark soil and refuse	Flags	Dry	13/3/23	2 ft. 9 in.	33·2
Sandy clay and sandstone ..	Flags	Dry	13/3/23	1 ft. 8 in.	13·0
Soil and clay	Flags	Dry	15/3/23	3 ft. 6 in.	18·8

the Newcastle district, given in Table 60 in the present report. These figures are not complete, and I am making further tests, as it will only be possible to make full use of the valuable information summarized in the report if one is able to plot a thermal resistivity (g)/moisture content curve for the different kinds of soil found in the district, and also to have a reliable figure to take as the average minimum moisture content throughout the year.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

North-Western Centre, at Manchester, 20 March, 1923.

Mr. H. A. Ratcliff: Most of my mild criticisms on the Preliminary Report are still more or less applicable to the present report. I then advocated starting with the super-tension cables on the principle of the greater including the lesser, for if we are satisfied that the 33 000-volt cables are safe the others may be said to look after themselves. The authors appear to have taken certain arbitrary values for the permissible working temperatures of the conductors, and two specific cases have been dealt with, viz. cables laid direct in the ground, and cables drawn into ducts. Having selected those arbitrary values, then, partly by calculation and partly by experiment, they have arrived at the loadings of the several cables which result in those conductor temperatures being attained. When the theoretical and experimental results did not agree they appear to have adjusted them until they did agree. There is no doubt that the first consideration is the maximum safe working temperature; that is really the crux of the whole matter, and the rest follows as a matter of course. I am inclined to think that in many cases the maximum safe temperature will never be attained, because for other reasons the cables concerned will never be loaded up to the values necessary to produce it. No attempt is made in the report to define the maximum safe temperature, and I should be glad if the authors in their reply would give rather more detailed reasons for the selection of the particular working temperatures, viz. 65° C. and 50° C., respectively. To what extent, in their opinion, do those temperatures allow for a reasonable factor of safety, such an essential feature of sound engineering work? The report contains a number of tables giving the permissible loadings for all the cables scheduled in B.S.S. No. 7, and for various pressures up to and including 11 000 volts, but if the tables are examined carefully it will be found that in most cases the differences between the loadings for the several pressures are very small. Such differences as occur appear to be within the limits of error which may naturally be expected to arise from the many variables with which the authors have had to contend. In any case the variations for different voltages are less than those resulting from such a comparatively indeterminate quantity as the resistivity of the ground. The most notable differences are between the loadings for the 2 200- and 3 300-volt cables laid direct in the ground, but, for some not very obvious reason, when the cables are in air there is very little difference between the loadings for the same two pressures. We have been laying 33 000-volt cables in Manchester for some years. When we first purchased them there were very few data available relating to safe loadings and working temperatures, but from such data as were available, and the results of experiments carried out at the cable makers' works, we arrived at the figure of 60° C. for the safe working temperature of 33 000-volt cables after allowing a margin for contingencies. The permissible loadings worked out on the basis of that temperature are very little different from many of the figures given in the report, having regard to the fact that we had no definite information relating to the resistivity of the ground. The following are typical values for the loadings of three-core, 33 000-volt cables: 0·1 sq. in.—165 amps.; 0·15 sq. in.—210 amps.; 0·25 sq. in.—280 amps.; 0·30 sq. in.—315 amps.; and 0·35 sq. in.—345 amps. Not having definite information as to the relative effect on the cable temperature of direct laying and drawing into ducts, it was decided to reduce the current density in cables drawn into ducts in the vicinity of the generating station and substations. In other words, the section of the cable was increased in those particular positions. The most noticeable difference between "duct" and "direct laid" conditions referred to in the report is the arbitrary one of 15 deg. C. between the permissible working temperatures. This temperature difference is of considerable importance, because it appears to represent a difference of about 12 per cent between the actual loadings of the cables under the respective conditions. The reduction in the maximum permissible temperature in the case of cables drawn into ducts appears to have been based mainly on mechanical considerations, and I should therefore like to have the authors' opinion of its applicability or otherwise to wire-armoured cables, since the best modern practice is to employ a wire armouring on lead-covered cables when they are to be drawn into ducts. One remarkable fact which emerges in this connection is that when cables are drawn into ducts the resistivity of the ground is more or less immaterial, and consequently the temperature conditions of the cable are the same over a comparatively large range of ground resistivity. Probably the most important feature of the report is the information relating to the short-time or emergency ratings, because as a rule in actual practice it is only under emergency conditions that cables are deliberately overloaded. Owing to the breakdown of a cable, for instance, it may be necessary to overload other cables to a very considerable extent for an hour or two, but in view of the information given in the report the risk attending such temporary overloading is negligible. The ultimate limits of loading will, I think, be fixed by considerations of either copper loss or dielectric loss, according to the working pressure of the cables. More information on the subject of dielectric losses is very desirable, as at present we are somewhat in the dark as to their cause and effects, and, consequently,

there is a tendency to make them somewhat of a bogy. One other limitation to the permissible loadings arises from the effects of contraction and expansion. At one time these effects were considered to be very troublesome, but I am inclined to the view that they are not so serious as is usually supposed, and the figures given in the report bear that out. I have come to the conclusion that many of the troubles due to contraction and expansion are the result of bad joints. Some recent experiments have shown that the ultimate strength of a well-made joint is comparable with that of the conductor, and therefore it is not very obvious why trouble should be expected with joints. The simplest joint on a three-core cable is the one made with plain sleeves or sweating ferrules, and tests have shown such a joint to be strong enough for all practical purposes, provided that the ferrules are fitted with grub screws. Although they do not in themselves contribute materially to the strength of the joint, the grub screws are very essential because they serve to maintain the ferrules and the conductors in rigid and intimate contact during the period when the solder is setting. The report contains much information relating to ground isothermals and temperature gradients, but only so-called virgin ground has been considered, and it would be interesting to know to what extent the various curves and formulæ are applicable to the ground in a large city under the road surface of which there is usually a miscellaneous collection of gas, water, and Post Office pipes, sewers, and even steam pipes and cellars. Another very important feature of the report is the experimental work relating to cables in multi-way ducts. The largest duct referred to is a six-way one, but I know of an 80-way duct, and I am at times inclined to wonder what are the conditions prevailing in the centre of such an extensive duct line. I was rather surprised to see that the three-core cables had the same temperature-rise when heated by the passage of either direct or alternating current. That result does not seem to be quite in accordance with general experience. The usually accepted figure for the increase in the I^2R losses, due to the eddies in the lead sheath, is 5 per cent. It may be possible, however, that a 5 per cent loss in the sheath has not very much effect on the maximum temperature of the cores. In the case of single-core cables now used to a considerable extent for extra-high-pressure circuits, the effect of the sheath losses becomes of very great importance. A figure of 10 per cent has been put forward for sheath losses in such cases, but actually it depends to an enormous extent on the spacing between the separate conductors. Recent experiments have shown that a sheath loss equal to 15 per cent of the core loss is about normal for close spacing, but the value rises very rapidly as the spacing is increased beyond 6 inches.

Mr. W. J. Medlyn: The report deals with difficulties caused by the expansion and contraction of power cables, due primarily to the heating effect of the currents transmitted. I understand that cases occur where power cables laid in pipes or ducts on a slope have a tendency to slip downhill when they expand, with the result that they are heavily strained at the upper end each time that contraction takes place on cooling, after the current is shut off or reduced in strength; and, apparently, repetition of the strains may cause fracture of the cable. No doubt such cases have come under the notice of the authors, and it would be interesting to know whether any satisfactory method of overcoming the difficulty has been devised. In this connection I should like to mention one point where there is some relationship between power cables and telephone cables. In a few cases in the Manchester and Liverpool district some of the lead-covered trunk telephone cables, measuring about 3 inches in diameter, laid in stoneware ducts of the type illustrated in Fig. 20, have shown a tendency to creep after the jointing has been completed. The joints in these cables are made in manholes in which the ducts are terminated. In a number of cases the pull has been sufficient to stretch the cable and force the joint into one end of the duct, thus causing the lead sheath to be fractured. The cases have generally occurred, not on pronounced slopes, but on fairly level ground. The exact cause of the trouble has not been definitely ascertained, but probably it may be due partly to temperature variation, and partly to the effects of the vibration caused by road traffic, the cable movement being generally in the same direction as the traffic on the particular side of the road concerned. The heating effect of the minute currents passing through the cable is, of course, negligible, and the temperature variations must therefore be due to atmospheric changes in the different seasons of the year. From conductor-resistance tests which have been made on some of the telephone cables in Lancashire it is calculated that there was a temperature variation of something like 11 deg. F. to 14 deg. F. as between summer and winter. In one case the temperature indicated on a thermometer placed in a duct 10 yards from the manhole was 65° F. in August as compared with 46° F. in November, a difference of 19 deg. F. I should be glad to know whether the authors, in the course of their research work, have included any observations of temperature effects in underground cables due to ordinary atmospheric changes, and, if so, how their figures compare with the results which I have mentioned.

Mr. A. B. Mallinson: The authors have referred to three systems: Cables laid in the air, cables laid in ducts, and cables laid direct in the ground. Under what rating would they classify cables laid solid in bitumen in wooden troughs, and cables drawn into fibre conduits? Are these to be classified as cables laid direct in the ground or as cables drawn into ducts? Have the authors done any experimental work on cables of different makes? It is only natural to assume that different makers sometimes employ different insulations, and that will have an effect upon the figures given in the report. On page 537 the interesting fact in cable laying is referred to, that in many cases a cable trench will for years act as a drain for the surrounding country. This is not often realized. It is very refreshing to hear the authors speak of cables loaded up to the limits permissible by heating. At a recent meeting at this Centre the advocates of automatic substations commented on the fact that most cables were not nearly fully loaded, and that there was no fear of them

getting hot for reasons other than the current loading of the cables.

Mr. B. Lakeman: I should be glad of some further information in regard to Tables 3 to 27. I am surprised that in the report the loadings of cables in the ground and in air are based upon two distinct temperature-rises, viz. 50 deg. C. and 35 deg. C. Do the authors propose to reduce the results to a common basic temperature-rise when issuing the final form of the results of their experiments? I consider that the usefulness of the tables would be thus enhanced.

Mr. A. R. Porter: Mr. Ratcliff has mentioned 80-way ducts in Manchester; these, I think, consist of 80 single-way fibre conduits laid in concrete. I should imagine that with a nest of single-way ducts laid either direct in the ground or in concrete, the temperature-rise would be much less than in the case of the multiple ducts illustrated in the report. In the former case there is a much greater space between the ducts than is afforded by the comparatively thin walls of multiple stoneware, and it seems possible that practically the conditions given for a single-way duct line may be approached. It is known that a sudden and intense rise of temperature due to a short-circuit may be rapidly conducted throughout a multiple duct similar to that illustrated, tending to destroy the other ducts. I believe that this is not the case with the nest construction mentioned, and it therefore seems probable that the conditions of temperature-rise would be similarly modified. Have the authors carried out any tests of these conditions?

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

South Midland Centre, at Birmingham, 4 April, 1923.

Mr. A. M. Taylor: In the investigation, in Appendix III, upon the relation between thermal resistance and electrostatic capacity, the comparison between the experimentally determined electrostatic capacity and the capacity as determined by Russell's formula and also by Mie's formula, and the investigation of its relation to the thermal resistance of the cable, are particularly interesting. In a recent paper * I pointed out that the reciprocal of the capacity (termed by Karapetoff the "elastivity") is related to the geometrical dimensions of the cable in a precisely similar way to the thermal resistance, and I am glad that the authors emphasize this point. The remarks on page 541 relating to the difference between the expansion of the armouring of the cable and that of the lead sheathing of the copper would indicate that there are forces tending to buckle the copper conductor directly a point of minimum mechanical strength is reached. This would occur where the cable approached a junction box, and might take place in the junction box itself. In one case which came to my notice the copper had been quite crushed up and forced into connection with the box itself by this action. The tremendous forces that obtain must result either in the armouring being inordinately strained or the copper being unduly compressed, and it is not inconceivable that, due to the worming of the three copper conductors, a tendency to sudden bending might occur in parts of the cable itself which would be sufficient, even though unnoticeable, to crack the insulation and start a weak point which would develop into a fault. This points to the advantage of, if possible, doing without the armouring altogether, a course which was adopted in the Gennevilliers cables. I should like some more information on the subject of six-conductor cables, particularly of the size consisting of six 0·185 sq. in. cores used as a split-conductor cable, corresponding to an area (per phase) of 0·37 sq. inch. Several such cables were used on the Birmingham system and any information as to the possibilities of increased current-carrying capacity would be most welcome. In Table 16 a current of 328 amperes is given for a 0·25 sq. in. cable (concentric and armoured), while in Table 21 a current of 344 amperes is given for a precisely similar cable, with the difference, however, that the latter was insulated for 11 000 volts whereas the former was insulated for only 660 volts. One would have expected that the thermal resistance of the 11 000 volt cable would have been much higher than that of the 660 volt cable, demanding a very much smaller current, rather than that a larger current would have been permissible. Will the authors explain this point? In Table 28 a figure of 620 is given for the resistivity of cable No. 3, and a figure of 1 060 for the resistivity of cable No. 4. There seems to be no obvious reason for this great difference. Again, it is stated on the same page that "examination of the experimental values for different types of cable showed that generally the lower-pressure cables had a thermal resistivity somewhat greater than the higher-pressure cables," and the remarks that follow seem to suggest that this is due to questions of cost. I should like to know whether it was in any way due to the fact that with the higher insulations there was a much greater distance through which impregnation had to take place, and whether the impregnation was possibly less perfect in the higher-voltage cables. In Table 39 the figure of 172 amperes is given for the safe current for a six-core 0·1 sq. in. cable. I would remind the authors that in Table 2 of the previous report the safe current for a precisely similar split-conductor cable was given as 284 amperes per core. I think that the latter figure was probably wrong, but I should like to know for certain that this is so, as the discrepancy is otherwise very serious. On page 546 it is stated, in dealing with triple-concentric cables, that if the load were assumed to be carried by the two inner conductors only, the current for a given temperature-rise would be 5 per cent less than that for the "equivalent" size of concentric cable with two conductors only. What would have been the result if the innermost and outermost conductors had been considered, the intermediate conductor carrying no current? I am interested in

* "The Possibilities of Transmission by Underground Cables at 100 000/150 000 Volts," *Journal I.E.E.*, 1923, vol. 61, p. 220.

a cable in which varying currents are carried in the different intersheaths, and my impression is that the greater the amount of heat that can be liberated towards the circumference of the cable, the lower will be the temperature of the innermost core. The expression "equivalent" used by the authors should also be defined. Do they mean by this the *same* cross-section for each of the two "outer" cores, or a cross-section such that the same power can be conveyed with the same *total* amount of copper at an equal voltage across the "outers"? In Table 1 are given particulars requiring further elucidation, and I am of opinion that the figures in heavy type, viz. 340, 180, 120 and 90 should preferably be, 227, 120, 80 and 60. I should like to see Equation (7) (page 523) extended in such a manner as to embrace triple-concentric cables in which there are various relations between the current in the central core and those in the outer cores.

Mr. H. W. Blades: It is very interesting to note from actual tests that there is no appreciable increase of heating in a three-core cable when loaded with three-phase current of varying periodicities, as compared with that occurring with direct current. One would naturally expect that the skin effect and the eddy currents in the lead sheath would have affected the results of the test to a certain degree. In dealing with the expansion of cables, an instance occurred a short time ago where a number of cables under abnormal war conditions gradually slipped for a distance of 4 ft. down a long gradient for a total distance of approximately 500 yards, but by taking advantage of the expansion of the cable when loaded, and by means of suitable clamps and straining devices, these cables were persuaded to creep uphill against the stiff gradient until they were back again in their original position. This was, of course, accomplished whilst the cables were carrying full load. On page 541 it is stated that "a cable drawn into a duct is free to move lengthways along the duct and cause injury to the lead by abrasion." From observations and tests on a large conduit system the chief trouble was found to be, not so much the question of the abrasion of the lead in contact with the duct, but how to accommodate the expansion of the cables and so prevent ripples in the lead and cracked plumbs, etc., in the joint pits. The linear expansion resulted in a longitudinal movement of the cable at the bell mouth, but by suitable bends in the cable at the joint pit this longitudinal movement was changed into a lateral movement of the joint box. The joint boxes are mounted on special cradles, and these are free to move in a transverse direction. Tests showed that these joints were in a state of continual movement. These joints have been working successfully for several years in this manner and there are no signs at all of the deterioration of the lead.

Mr. W. E. Groves: The information in the report is exactly what the mains engineer needs. It is most useful in stating concisely the factors to be reckoned with in assessing the rating of cables. Although the effects of the various conditions or circumstances of cable-laying are in most cases what were to be expected, the precise information is most useful in fixing the degree of importance to be given to each governing factor. In some instances, however, the experiments give results which are not only enlightening but also quite unexpected. As the permissible current loading is generally governed by the maximum temperature which can be attained without damage to the dielectric, it is hoped that more definite information will be forthcoming on this point. Meanwhile, the limits given will be in the mind of the engineer, who will realize that they must necessarily be safe as they are stated to be permissible in a report to which great weight will be attached. The thermal resistivity of the dielectric will obviously be constant throughout a cable length, but in considering a long run of main the safe loading will, from the point of view of thermal resistivity, depend on the worst patch of ground that it passes through. Consequently, in determining the load rating of the cable before laying, the least favourable conditions must be assumed. In this connection, one would expect that the nature of the paving would affect the moisture content of the ground. Modern methods of treatment of roadways render the surface practically impervious to moisture, and the surface water is much more thoroughly drained to the sewers. It is interesting to note that the mechanical strains due to expansion are considered among the limiting factors. Considerable ingenuity has been brought to bear on the countering of these effects and it is to be hoped that ultimately the permissible temperature will be limited solely by the effect on the dielectric properties of the insulation. This limitation due to expansion is emphasized in the writing down of the permissible temperature of cables in conduits by 15 degrees C. in order to avoid abrasion of the lead. This appears to be hardly justified if the internal surface of the conduit is smooth and well-lubricated when the cable is drawn in. At any rate it seems too high a price to pay and one would rather risk a little, as the damage would be more local than that caused to the cable by overheating of the dielectric. Conduits are an unfortunate necessity in many cases and it is both interesting and surprising to learn that the experiments show that the temperature of the cable is not materially affected by the relative dimensions of cable and conduit. The publication of the results of exhaustive research, and formulæ for calculating the effect of practically all possible conditions of mains laying, should result in more scientific practice than has hitherto obtained.

[The reply of Messrs. S. W. Melsom and E. Fawssett to this discussion will be published later.]

REPORT OF THE COUNCIL FOR PRESENTATION AT THE ANNUAL GENERAL MEETING OF 31 MAY, 1923.

CONTENTS.

REPORT.

The Council, at the Fifty-first Annual General Meeting of the Institution of Electrical Engineers, present to the members their Report for the year 1922–23, covering approximately the period 1 April, 1922, to 31 March, 1923, and, in doing so, desire to put on record their gratification at the continued progress of the Institution.

(1) Bye-Laws.

The Bye-Laws for the Chartered Institution which were approved at a Special General Meeting of Corporate Members held on the 23rd March, 1922, received the sanction of the Lords of the Privy Council on the 1st June, 1922. Members who have not already received a copy can obtain one on application to the Secretary.

(2) Liquidation of Old Institution.

The process of transferring to the Chartered Institution the property of the old Institution, including the trusts in connection therewith, has proved more protracted than had been anticipated, chiefly owing to certain provisions in some of the trust deeds necessitating, on the dissolution of the old Institution, steps being taken to ensure that these trusts and the benefits under them should pass to the Chartered Institution. For that reason, the final winding-up must necessarily be postponed a short time longer until the whole of these trusts and benefits have been transferred to the new Institution.

(3) Membership of the Institution.

The changes in the membership since the 1st April, 1922, are shown in a table which will be found in Appendix A.

The following table shows the growth of membership for the last few years:—

Year	Membership	Increase or Decrease.
1913	7 084	—
1914	7 045	− 39
1915	6 811	− 234
1916	6 676	− 135
1917	6 613	− 63
1918	6 667	+ 54
1919	7 023	+ 356
1920	8 146	+ 1 123
1921	9 449	+ 1 303
1922	10 275	+ 826
1923	10 911	+ 636

It will be seen from the above that, while the decrease in membership during the war period was 471, the increase since the war has amounted to 4 298.

The Council have noticed with satisfaction the practice of some employers of stipulating Corporate Membership of the Institution as a qualification for vacant positions, and urge its adoption by all employers.

(4) Examinations.

The Associate Membership Examination was held in April and October, 1922, in London, Chatham, Birmingham, Manchester, Newcastle-upon-Tyne and Cardiff, and also abroad in New Zealand, South Africa and Australia. The candidates examined included a number of officers of the Corps of Royal Engineers who sat for the examination for the purpose of qualifying for "Engineer Pay."

A certain number of candidates submitted theses and papers during the year in lieu of the examination.

For the purpose of qualifying for "Signal Pay," Officers of the Royal Corps of Signals were examined by the Institution, in the "Theory of Electrical Military Signalling" at the Signal Service Training Centre, Maresfield Park Camp, Sussex, in August, 1922, and February, 1923.

(5) Honorary Members.

The Council have pleasure in recording that, as announced at the Ordinary Meeting of the 16th November, 1922, they have elected Professor John Ambrose Fleming, M.A., D.Sc., F.R.S., to be an Honorary Member of the Institution. The number of Honorary Members now stands at 10.

(6) Honours and Distinctions Conferred on Members.

Since the last Annual Report the following honours have been conferred on members:—

Baronetcy.

Drummond, Brig.-Gen. H. H. J., C.M.G. (Associate).
Sutton, George (Member).

K.B.E.

Lewis, H. D. W. (Member).

Knighthood.

Hughman, E. M. (Associate).
Manville, E., J.P., M.P. (Member).

C.B.

Wray, Capt. T. H. Roberts, O.B.E., R.N.V.R. (Associate Member).

C.V.O.

Hussey, Major W. C., R.E. (Associate).

(7) Faraday Medal.

To commemorate the 50th anniversary of the foundation of the Institution (under the name of the Society of Telegraph Engineers) the Council decided last year to establish a "Faraday Medal" in bronze to be awarded by the Council not more than once a year for "notable scientific or industrial achievement in Electrical Engineering or for conspicuous services rendered to the advancement of Electrical Science without restriction as regards nationality, country of residence or membership of the Institution."

The Council selected for the first award of the medal Mr. Oliver Heaviside, F.R.S., who, unfortunately, owing to ill-health, was unable to attend a meeting of the Institution to receive the medal, which was personally presented to him by the then President, Mr. J. S. Highfield, at Torquay on the 9th September, 1922.

The second award of the medal has been made by the Council to the Hon. Sir Charles Algernon Parsons, K.C.B., F.R.S.

(8) War Memorial.

The unveiling and dedication of the War Memorial in the Institution Building in memory of the members of the Institution who lost their lives in the War of 1914–18 took place on Wednesday afternoon, 28th June, 1922. The Memorial is in the form of two bronze panels, containing the names of 162 fallen members, designed by the Institution's architect, Mr. H. Percy Adams, F.R.I.B.A., and modelled by The Birmingham Guild, Ltd., and fixed respectively on the East and West walls of the Entrance Hall.

A full account of the ceremony is contained in the *Journal*, vol. 60, p. 948.

The War Memorial Book containing the biographical notices and portraits of the fallen members will, it is hoped, be published in the course of the year.

Out of the balance of the above Fund it has been decided to establish two scholarships, each of the value of £50 per annum and tenable for three years, to provide for the education of children of those members of the Institution who were killed or permanently disabled in the War.

(9) Deaths.

The Council have to deplore the death of the following 48 members of the Institution during the year.

Honorary Member.

Bell, Professor Alexander Graham.

Members.

Claremont, E. A.	Miller, H. W.
Craig, J. H.	Robinson, M. H.
Darby, J. C. H.	Sharp, S.
Dewar, Prof. Sir James, M.A., F.R.S.	Suckling-Baron, A. I.
	Talbot, F. F.
Fraser, J.	Trouton, F. T., M.A., D.Sc., F.R.S.
Gavey, Sir John, C.B.	
Godfrey, W. B.	Ward, G. G.
Kapp, Prof. Gisbert.	Webb, G. R., M.B.E.
Willis, R. H.	

Associate Members.

Bates, W., O.B.E.	Kirk, M.
Bish, G. J.	McAlonan, D.
Bradbury, R. H.	McKee, F. J.
Clunas, J. F.	Martin, J.
Dobson, J.	Mitchell-Cocks, J.
Emmott, H.	Ogilvie, W.
Gill, D.	Roberts, P. A.
Healy, L. T.	Stobie, H. E.
Jephson, R. P.	Thomas, G. T.

Walter, L. H., M.A.

Graduates.

Hollinrake, J. S.	Palmer, W. G.

Students.

Ablett, L.	Cox, W. L.
Ash, R. H. H.	Davis, G. C. C.

Langley, H. W.

Associates.

Barrett, A.	Parsons, The Hon. R. C.
Hassard, Lt.-Col. H. S.	Walmisley, A. T.

Of the foregoing, the Institution has suffered especially in the loss of the following distinguished members :—

Sir John Gavey, C.B. (Member of Council 1899–1900 and 1904, Vice-President 1901–1904, President 1905) ; Professor Gisbert Kapp (Member of Council 1886, 1889–1891, 1893–1896, Chairman of the Birmingham Local Section 1907, Vice-President 1907, President 1909) ; Professor Alexander Graham Bell (elected Member 1877 and Honorary Member 1913) ; Mr. Sidney Sharp (Member of Council 1890 and Honorary Auditor 1904–1918) ; Mr. H. Woodville Miller (Member of Council 1896–1898) ; Mr. M. H. Robinson (Member of Council 1901–1903) ; Mr. G. G. Ward (Local Honorary Secretary and Treasurer for the U.S.A. 1876–1922) ; and Prof. Sir James Dewar, M.A., F.R.S. (elected Member 1881).

(10) Institution Building.

The Council are highly gratified at the continued use of the Institution theatre and rooms by a very large number of allied and kindred societies.

(11) Meetings and Papers.

A statement of the total number of meetings and conferences held during the past twelve months and of papers read, lectures, etc., will be found in Appendixes B and C to this Report.

In this connection, the Council gladly refer again to the generous devotion by members of the Institution of their time and expert knowledge to the work of its various Committees.

The Premiums awarded by the Council for papers will be announced at the Annual General Meeting, or as soon as possible thereafter.

(12) Ordinary Meetings.

The discussions have been consistently maintained at a high level, and have been more spontaneous than in the past. The Council wish to tender the best thanks of the Institution to the various speakers who place their knowledge and experience at the disposal of their fellow members by reading papers or taking part in the discussions.

As regards the attendances at the meetings, the fact that, owing to the many Centres and Sub-Centres of the Institution, the same paper is read at several places, appears to react unfavourably on the attendance at any particular meeting, a result which, in the case of highly technical papers, may need consideration in the future.

(13) Local Centres and Sub-Centres.

In accordance with the Bye-Laws of the Chartered Institution, the former designation of "Territorial Centre" has been changed to "Local Centre."

The Reports of the various Centres show that the attendances at their meetings have been satisfactory.

During the Session the President paid visits to the Centres at Birmingham, Bristol, Dublin, Glasgow, Leeds, Manchester and Newcastle-upon-Tyne, and to the Sub-Centres at Liverpool, Loughborough, Middlesbrough and Sheffield.

On the 1st February, 1923, the Council granted a petition for the formation of a Centre at Liverpool, in place of the former Sub-Centre.

(14) Technical Libraries for Local Centres.

The Council decided during the Session to supply technical books to the value of £50 to any Centre wishing to set up a Technical Library, provided that suitable accommodation is available, and that each collection is maintained and added to locally, the books remaining the property of the Institution.

(15) Local Honorary Secretaries Abroad.

During the Session the Council appointed Mr. Gano Dunn, a Past-President of the American Institute of Electrical Engineers, to be Local Honorary Secretary for the United States of America, in place of the late Mr. G. G. Ward.

The Council also appointed Mr. M. L. Kristiansen, Chief Engineer of the Kristiania Government Telephone Service, to be Local Honorary Secretary for Norway.

(16) Wireless Section.

The Wireless Section of the Institution has held eight meetings, at which nine papers were read.

(17) Informal Meetings.

The Informal Meetings during the past Session have maintained their interest and, though the average attendance was below that of last year, the subjects selected have been keenly debated.

On the score of assisting in the training of speakers, the Informal Meetings have undoubtedly well served their purpose this Session, and a number of new speakers have contributed to the discussions.

The Annual Smoking Concert was greatly enjoyed by the large audience which attended, and the Benevolent Fund has benefited by the proceeds.

(18) STUDENTS' SECTIONS.

The number of Students on the Register of the Institution has reached a record total of 2 869, representing 26 per cent of the total membership.

A very full programme of meetings, visits to works, and social functions was carried out during the Session by the eight Students' Sections now in existence, viz. in London, Birmingham, Glasgow, Leeds, Liverpool, Manchester, Newcastle and Sheffield.

Addresses to the London Students' Section were given by the President and Mr. C. H. Wordingham, C.B.E., Past-President.

A Students' visit to Cardiff and district, organized by the London Students' Section, took place from the 24th to the 28th July, 1922. The following works were visited: The Melingriffith Tin Plate Works, Messrs. Vivian's Hafod Copper Works, Messrs. Baldwin's Landore Steel Works, The Britannia Colliery, The Barry Docks (G.W. Rly.), Messrs. Lewis and Mayer's Cement Works.

The Council have cordially thanked the firms named for the courtesy shown by them on the occasion, and for the facilities afforded, which very materially helped to make the visit an acknowledged success.

The Council have also thanked Mr. J. H. Reyner (Honorary Secretary, London Students' Section) for his valuable work in organizing the visit.

(19) SCHOLARSHIPS.

The following Scholarships have been awarded by the Council:—

David Hughes Scholarship.
(Value £40; tenable for one year.)
W. H. M. Hellier (University College, Cardiff).

Salomons Scholarship.
(Value £50; tenable for one year.)
A. H. Maggs (Bristol University).

Paul Scholarship.
(Value £50; tenable for one year.)
C. A. Wilck (Finsbury Technical College).

War Thanksgiving Education Research Fund (No. 1).

A grant of £100 for educational purposes has been made this year by the Council under the provisions of the Trust Deed to R. H. Holmes (Armstrong College, Newcastle-upon-Tyne).

(20) CONVERSAZIONE.

The Annual Conversazione was held at the Natural History Museum, South Kensington, London, on the 29th June, 1922, when there was a record attendance of over 1 700 members and guests.

(21) ANNUAL DINNER.

The Annual Dinner was held at the Hotel Cecil, London, on the 6th February, 1923, the members and guests present numbering 480.

A message was received from H.R.H. The Prince of Wales regretting his inability to be present, and among the distinguished guests present were the following who spoke: The Rt. Hon. Neville Chamberlain (Postmaster-General), Sir W. Joynson-Hicks, Bart., M.P. (Parliamentary Secretary to the Overseas Department of the Board of Trade), and Sir Arthur Colefax, K.B.E., K.C.

An account will be found in the *Journal*, vol. 61, p. 400.

(22) SUMMER MEETING.

The Summer Meeting in Scotland, admirably organized by the Committee of the Scottish Centre, took place from the 30th May to the 2nd June, 1922, and was very successful. A short account of the meeting will be found in the *Journal* (1922, vol. 60, Institution Notes, p. 26).

(23) PORTRAITS OF PAST-PRESIDENTS.

The Council have arranged for a complete set of enlarged photographs to be made of the Past-Presidents of the Institution. These, suitably framed, will be hung in the Institution's rooms as soon as the collection is complete.

(24) CONVENTION OF AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS AT NIAGARA.

At the above convention held at Niagara from the 26th to the 30th June, 1922, the Institution was represented by Mr. A. P. M. Fleming, C.B.E.

(25) ASSOCIAZIONE ELETTROTECNICA ITALIANA.

Signor Guido Semenza, the Institution's Local Honorary Secretary for Italy, represented the Institution at the celebration of the 25th Anniversary of the foundation of the Association last September.

(26) KONINGLIJK INSTITUUT VAN INGENIEURS.

Similarly, the Institution was represented by Mr. P. V. Hunter, C.B.E., at the celebration of the 75th Anniversary of the foundation of the Royal Institute of Engineers at The Hague.

(27) LIBRARY.

During the year 235 books and pamphlets have been presented to the Reference Library by members and others. A marked increase in attendance is recorded, the total number for the year being 2 526, of whom 125 were non-members, as against the previous highest yearly total of 1 651 in 1915–16.

The Council have pleasure in recording a continued increase in the circulation of books from the Lending Library. During the year 2 213 were issued to 814 borrowers, the corresponding numbers for the previous year being 1 450 and 564 respectively.

(28) MUSEUM.

After carefully considering the question of exhibiting the historical apparatus, particularly the larger appar-

atus and heavy machinery, the Council decided, in view of the limited space available in the Institution Building for this purpose, to offer to loan the collection, or such part of it as would be acceptable, to the Science Museum, South Kensington. The offer has been accepted and a considerable portion of the historical objects has now been transferred to the Science Museum.

By exhibiting the apparatus in a public Museum the Council feel that it will receive wider publicity, especially taking into consideration that a considerable number of the transferred objects would otherwise have had to remain stored in the basement of the Institution for an indefinite period.

In view of this arrangement the Council can in future accept apparatus only on the understanding that, on the recommendation of the Museum Committee, it may be transferred on loan to the Science Museum.

The following objects have been presented during the past year, and the Council desire to express their thanks to the donors :—

List of Apparatus.	*Presented by*
Four examples of Navy telephones.	The Lords Commissioners of the Admiralty.
A collection of obsolete telegraph and telephone apparatus (14 objects).	The Engineer-in-Chief of the General Post Office.
A Holmes arc lamp dismantled from South Foreland Lighthouse.	The Elder Brethren of Trinity House.
An Ayrton-Perry magnifying spring voltmeter.	The Delegacy of the City and Guilds (Engineering) College.
An Ayrton-Perry magnifying spring ammeter.	The Delegacy of the City and Guilds (Engineering) College.
An Ayrton-Perry motor.	Professor T. Mather, F.R.S.
An Ayrton-Perry permanent magnet ammeter.	Professor T. Mather, F.R.S.
An Ayrton-Perry permanent magnet voltmeter.	Professor T. Mather, F.R.S.
A Serrin arc lamp.	The Committee of the Liverpool Public Libraries.
A Lorain contact-box.	C. Owen Silvers.
A collection of early telephone apparatus (21 objects).	F. G. C. Baldwin.

(29) Electrical Appointments Board.

During the past year there has been a gradual increase in the number of applicants for posts, the total being 130 as against 120 last year.

A classified Register of members seeking positions, containing particulars of their training and experience, is available for inspection at the Institution offices, and the Secretary of the Board will gladly put employers into touch with highly qualified electrical engineers in practically all branches of the profession.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the Register.

Vacancies may also be reported to the Honorary Secretaries of Local Centres and Sub-Centres, who will at once report such vacancies to the Secretary of the Board at the Institution offices.

(30) The Journal of the Institution.

The number of pages in the 1922 Volume was 1 002 (excluding 18 plates of half-tone illustrations), as compared with 852 pages in 1921. The large increase in the number of pages was due to the Special Number of the *Journal* containing an account of the proceedings at the Commemoration Meetings held in February, 1922.

The net cost of printing and publishing the *Journal* in 1922, after allowing for sales, was £4 604, as compared with £4 936 in 1921. This reduction is all the more gratifying when the large increase in the number of copies and the amount of matter printed is taken into account.

(31) Advertisements in the Journal.

The Council's intention of publishing in the *Journal* a Classified Index of British Manufacturers, which was referred to in the last Report, could not for a number of reasons be proceeded with, but in reconsidering the position the Council felt that it was in the best interests of the Institution to revert to the practice which obtained until 1913 of publishing advertisements in the *Journal*. A beginning was accordingly made with the March number, and the *Journal* will in future contain advertisements.

(32) "Science Abstracts."

The Council deeply regret to have to record the death in September last of Mr. L. H. Walter, M.A., who had been Editor of *Science Abstracts* since 1903. In his place, the Council have appointed Mr. W. R. Cooper, M.A., B.Sc., to be the Editor of the publication.

The Physics volume of *Science Abstracts* for 1922 contained 104 more pages than that for 1921, and the Electrical Engineering volume, 8 more pages.

The contribution of the Institution towards the cost of publishing *Science Abstracts* in 1922 was £1 085, as compared with £978 in 1921. This increase was not expected in the earlier part of the year, but was rendered necessary by the large amount of belated material which came from the Continent after the War. The position is now becoming more normal in this respect. The Committee of Management have also taken steps to increase the revenue of *Science Abstracts* so that the burden falling on the Institution should be materially less in the future.

(33) Wiring Rules.

Owing to the many divergencies of view and the large number of amendments made to the Preliminary Draft, it has been impossible to complete the revision of the Rules during the Session under review. It is hoped that the Committee will be able to report finally on this matter at an early date.

(34) MODEL CONDITIONS FOR CONTRACTS.

The Council have appointed a Committee to prepare Model Conditions of Contract for :—

(a) "Home" orders when no erection is included in the contract;
(b) "Export" orders, with or without erection.

The above are still under consideration by the Committee and, it is hoped, will shortly be published.

(35) BRITISH ELECTRICAL PROVING HOUSE.

The Committee appointed by the Council to report on the question of setting up a National Proving House for the testing of electrical goods and materials have not yet completed their Report. Some progress has been made with the preparation of a scheme for the purpose, and other bodies interested in the matter have been consulted.

(36) VOLUNTARY REGISTRATION OF ELECTRICAL CONTRACTORS.

A scheme to give effect to the above has been prepared by the Committee appointed for the purpose and has been approved by the Council. The scheme provides for a Registration Authority consisting of nominees of the Institution and of interested bodies which will carry out as a separate body the registration of Electrical Wiring Contractors.

(37) ELECTRICITY REGULATIONS.

The Regulations Sub-Committee of the Power Lines Committee has been given the status of a Committee under the name of the Electricity (Supply) Regulations Committee, and as a consequence the original Power Lines Committee, together with its two Sub-Committees (Wayleaves and Factors of Safety), has been dissolved. A set of draft Regulations for Low and Medium Pressure Overhead Lines, prepared by the Committee was circulated to the Associations concerned and, after revision, was, together with a set of draft Regulations for High Pressure Lines, submitted on behalf of the Council to the Electricity Commissioners for their approval.

The Committee are now considering amendments to the Board of Trade Regulations, (a) for securing the safety of the Public, and (b) for ensuring a proper and sufficient supply of Electrical Energy, for the purpose of enabling the Council to submit a Report thereon to the Electricity Commissioners.

(38) COMMITTEE ON ELECTRICITY IN AGRICULTURE.

The Council have appointed a Committee as above, with the following terms of reference :—

To consider and report to the Council on the following points :—

(a) Whether there are any special features in connection with the supply and use of electricity in agriculture which need special attention from the Institution by way of education or propaganda, and, if so, what action the Committee recommend the Council to take;

(b) And for the purpose of making a recommendation :—

(i) To investigate and report upon the actual or probable load factors and annual consumption of farms in this country and elsewhere, and on the capital cost to Supply Authorities of supply to farms, and to farmers of the machinery for utilizing the supply, and of the economic results likely to be obtained by Supply Authorities and farmers;
(ii) To report on the desirability of a permanent Sectional Committee of the Institution for dealing with this question.

(39) IRISH FREE STATE.

As the result of representations made by the Committee of the Irish Centre, the Council have authorized that Committee to appoint, on behalf of the Irish Free State Government, a Committee to advise, if requested, the Irish Government on matters concerning Electrical Engineering. This Advisory Committee has been appointed.

(40) BRITISH MANUFACTURED GOODS.

During the year under review the Council were in communication with the National Federation of Iron and Steel Manufacturers, and the following Resolution was passed by the Council at a meeting held on the 1st February, 1923 :—

"In view of the present state of trade and employment, the Council request members who place, or who advise upon the placing of orders, to specify as far as practicable that the plant and material ordered shall be of British manufacture."

Similarly, the Federation has agreed to recommend its members as far as possible to place orders for electrical material with British firms for British material.

(41) ELECTRICAL ENGINEERING TRAINING IN TECHNICAL SCHOOLS.

The scheme for the issue of certificates and diplomas to students who are trained and pass certain examinations under conditions approved by the Board of Education and the Institution, which was approved by the Council last Session, has since been approved by the Board. The Joint Committee of representatives of the Board of Education and the Institution provided for under the scheme has been set up and certain courses of training and examination syllabuses and schools have been approved. It is expected that the scheme will come into operation for the educational session of 1923–24.

(42) ENGINEERING JOINT COUNCIL.

As the result of a conference summoned by the Institution of Civil Engineers, which was attended by representatives of that Institution, and of the Institutions of Electrical Engineers, Mechanical Engineers, and Naval Architects, an Engineering Joint

Council has been set up, the constitution of which is still under consideration and is provisionally as follows :—

1. A Council to be entitled "The Engineering Joint Council" shall be formed. It shall consist of two members of the Council of each of the following Institutions in the first instance, appointed from time to time by their Councils severally :—

The Institution of Civil Engineers,
The Institution of Mechanical Engineers,
The Institution of Naval Architects,
The Institution of Electrical Engineers,

which shall be called the Founder Institutions.

2. The Members of the Joint Council shall be appointed annually, and shall be eligible to serve for not more than four years consecutively. One of the first two appointed by each Institution shall serve for not more than two years, but shall be eligible for reappointment for a further period of not more than four years consecutively.

3. The Chairman shall be elected annually by the Joint Council, and the Secretary of the Institution represented by the Chairman for the year shall act as Secretary of the Joint Council. The Chairman shall be chosen from the several Institutions in rotation.

4. The Joint Council shall consider matters referred to it by the Council of any one of the constituent Institutions. It shall not initiate proposals affecting the Institutions, and shall be an advisory body without executive powers. Provision is also made in the draft Bye-Laws for the admission of other Institutions or Societies to representation on the Joint Council, subject to certain conditions.

(43) Electrical Research Association.

The Electrical Research Association has made good progress on all the researches in hand. A comprehensive Report on the heating of buried cables has been published by the Institution, which should lead to the saving of very large sums by Electric Supply Authorities. The work on insulating oils has resulted in the forthcoming issue of a British Standard Specification.

The researches on electric control apparatus are establishing new criteria of design. The work on overhead line materials has furnished new data which have been placed at the disposal of the Institution. A general levelling up of insulating materials of all kinds is being effected, and attention is being directed to the development of new materials with improved characteristics. Researches for the improvement of steam turbines and condensers have been extended.

The Institution has increased its annual subscription from £200 to £300, a corresponding grant being obtained from the Department of Scientific and Industrial Research.

Members are invited to communicate with the Director of the Association at 19, Tothill-street, Westminster, S.W.1, on the work of the Association and all matters relating to co-operative research.

(44). The British Engineering Standards Association.

Progress in connection with the Standardization of Electrical Materials and Apparatus has been steady during the past year and the following British Standard Specifications were issued :—

B.S.S. No. 7. Insulated Annealed Copper Conductors for Electric Power and Light.
B.S.S. No. 96. Parallel-Sided Carbon Brushes.
B.S.S. No. 109. Air-Break Knife and Laminated Brush Switches.
B.S.S. No. 1110. Air-Break Circuit Breakers.
B.S.S. No. 152. Metric Dimensions of Insulated Annealed Copper Conductors for Electric Power and Light.
B.S.S. No. 156. Enamelled Plain Copper Wires.
B.S.S. No. 168. Electrical Performance of Industrial Electric Motors and Generators (in place of No. 72 withdrawn).
B.S.S. No. 174–184. Overhead Line Wire Material for Telegraph and Telephone purposes.

The Specification for Insulating Oils for use in Transformers, Circuit Breakers, etc., has been approved and is in the printers' hands.

Progress has also been made in the preparation of the list of terms and definitions for use in Electrical Engineering. This list, which is an extension of that prepared by the Institution some few years ago, now comprises some 1 200 terms and, it is hoped, will be published shortly.

(45) The International Electrotechnical Commission.

Meetings of the Advisory Committees on Rating of Electrical Machinery, Symbols, Standard Pressures for Distribution and Insulators and Screw Lamp Caps and Holders were held in Geneva last November and good progress has been made in the various subjects under review. Of the representatives of the Institution on the British National Committee of this Commission Colonel R. E. Crompton, C.B., and Mr. Roger T. Smith attended the meetings.

(46) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1922, the Capital Account of the Fund stood at £9 969 11s. 3d., and the accumulated income at £1 463 1s. 3d. The donations and subscriptions to the Fund in 1921 amounted to £2 399 13s. 4d.

In the course of the year 40 grants were made to 16 persons, amounting to a total of £776 5s. 0d.

With a view to increasing the subscriptions to the Fund, the Committee have appointed a Local Honorary Treasurer of the Fund for each Local Centre of the Institution and also for the Sheffield Sub-Centre.

(47) Annual Accounts.

The Annual Accounts for the year 1922 will be found on pages 604 to 609 of No. 318 of the *Journal.*

Excess of Income over Expenditure.—After making provision for contingencies as in the previous year, there is a margin to the good on the Revenue Account for 1922 of £862 2s. 8d. This amount, which has been carried to the credit of the General Fund, compares with £639 2s. 10d. in 1921, an increase of £222 19s. 10d.

Mortgages.—

	£	s.	d.
In the Accounts for 1921 these stood at	24 331	19	11
Amount of repayments during the year	3 993	13	6
They now stand at	20 338	6	5

Life Compositions Fund.—The total of the Fund on the 1st January, 1921, was £5 590 10s. 0d., and an amount of £94 8s. 3d. was received for Life Compositions during the year. There being no obligation under the Bye-Laws of the Chartered Institution to keep these in a separate fund, the whole of these amounts has been transferred to the General Fund.

Assets.—Taking the Tothill Street property and the investments at cost, and the Institution Building and lease, the library and furniture, etc., at the values standing in the books after writing off depreciation—

	£	s.	d.
the Assets amount to	120 430	1	2
against Liabilities	6 030	19	1
leaving a surplus of	£114 399	2	1
which, in comparison with that of the year 1921, viz.	108 939	7	11
shows an improvement of	£5 459	14	2

The balance of £114 399 2s. 1d. is made up as follows :—

	£	s.	d.	£	s.	d.
Assets.						
Properties.						
Institution Building and Tothill Street Property	92 289	3	11			
Less Mortgages ..	20 338	6	5			
				71 950	17	6
Investments, Cash, etc.				41 886	18	9
Stock of Paper, Libraries and Furniture ..				6 592	4	11
				£120 430	1	2
Less *Liabilities.*						
Trust Fund Income Accounts	360	19	4			
Sundry Creditors ..	4 062	3	2			
Repairs Suspense Account	1 261	5	1			
Subscriptions received in advance	346	11	6			
				6 030	19	1
				£114 399	2	1

(48) THE INSTITUTION AND BODIES ON WHICH IT IS REPRESENTED.

For convenience of reference, there is attached hereto (Appendix D) a diagram showing the organization of the Institution and its representation on other bodies.

APPENDIX A.

MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since the 1st April, 1922, are shown in the following table :—

	Hon. Mem.	Mem.	Assoc. Mem.	Grad.	Studt.	Assoc.	Total.	TOTAL.
Totals at 1 April, 1922	10	1 800	4 661	934	2 455	415		10 275
Additions during the year :—								
Elected ..	..	16	157	144	692	9	1 018	
Reinstated ..	..	5	4	1	18	..	28	
Transferred to	1	68	87	79	..	..	235	
Total	1	89	248	224	710	9	1 281	
Deductions during the year :—								
Deceased	1	17	19	2	5	4	48	
Resigned	..	16	33	16	55	9	129	
Lapsed	..	6	60	41	122	4	233	
Transferred from	..	1	62	43	114	15	235	
Total	1	40	174	102	296	32	645	
Net Increase								636
Totals at 1 April, 1923	10	1 849	4 735	1 056	2 869	392		10 911

APPENDIX B.

MEETINGS.

The following is a list of the meetings held during the past twelve months :—

Ordinary Meetings ..	17
Wireless Sectional Meetings	8
Informal Meetings ..	8
Council Meetings ..	19
Local Centres :—	
Irish	9
Mersey and North Wales (Liverpool) ..	10
North-Eastern ..	11
North Midland ..	12
North-Western ..	13
Scottish	10
South Midland ..	11
Western	10
Local Sub-Centres :—	
Dundee	6
East Midland ..	10
Sheffield	6
Tees-side	8
Students' Sections :—	
London	9
Birmingham	11
Leeds	6
Liverpool	10
Manchester	8
Newcastle	15
Scottish	6
Sheffield	11
Committees :—	
Benevolent Fund ..	9
Electricity (Supply) Regulations ..	26
Examinations ..	7
Finance	13
General Purposes ..	8
Informal Meetings ..	8
Local Centres ..	2
Membership	7
Model General Conditions (and Sub-Committee)	6
Papers (and Sub-Committee) ..	8
Proving House Sub-Committee	1
Registration of Electrical Contractors ..	3
"Science Abstracts"	6
War Memorial ..	2
Wireless Section ..	5
Wiring Rules ..	8
Other Committees ..	6
Total	369

APPENDIX C.

Addresses.

Author.	Title.
R. D. Archibald, Member	Chairman's Address (Dundee Sub-Centre).
F. G. C. Baldwin, Member.	Chairman's Address (North-Eastern Centre).
A. S. Barnard, Member.	Chairman's Address (North-Western Centre).
Prof. W. Cramp, D.Sc., Member.	Chairman's Address (South Midland Centre).
F. Gill, President.	Inaugural Address.
F. Gill, President.	Address to the London Students' Section.
A. S. Hampton, Member.	Chairman's Address (Scottish Centre).
E. C. Handcock, Member	Chairman's Address (Irish Centre).
J. S. Highfield, Past-President.	Address to the Western Centre.
J. F. Nielson, Member.	Address to the Scottish Students' Section.
W. Pearson, Associate Member.	Chairman's Address (East Midland Sub-Centre).
W. P. Richmond, Associate Member.	Chairman's Address (Tees-side Sub-Centre).
F. Tremain, Member.	Chairman's Address (Western Centre).
B. Welbourn, Member.	Chairman's Address (Liverpool Sub-Centre).
H. West, Associate Member.	Chairman's Address (Sheffield Sub-Centre).
W. B. Woodhouse, Member.	Chairman's Address (North Midland Centre).
C. H. Wordingham, C.B.E., Past-President.	Address to the London Students' Section.

Lectures, Etc.

E. E. Brooks, Associate Member.	Exhibition of Lantern Slides illustrating Lines of Electric Force.
F. Creedy, Associate Member.	"Variable-Speed Alternating-Current Motors without Commutators."
Prof. M. Maclean, D.Sc., LL.D., F.R.S.E., Member.	"Hydro-Electric Resources of the Scottish Highlands."
R. B. Mitchell, Member.	"The Dalmarnock Power Station."
Dr. H. W. Nichols.	"Transoceanic Wireless Telephony."
Sir E. Rutherford, F.R.S.	"Electricity and Matter" (The Thirteenth Kelvin Lecture).
A. G. Warren, Member.	"The X-Ray Examination of Materials."
B. Welbourn, Member.	Exhibition of cinematograph films on "The Electrification of the Chicago, Milwaukee and St. Paul Railroad."

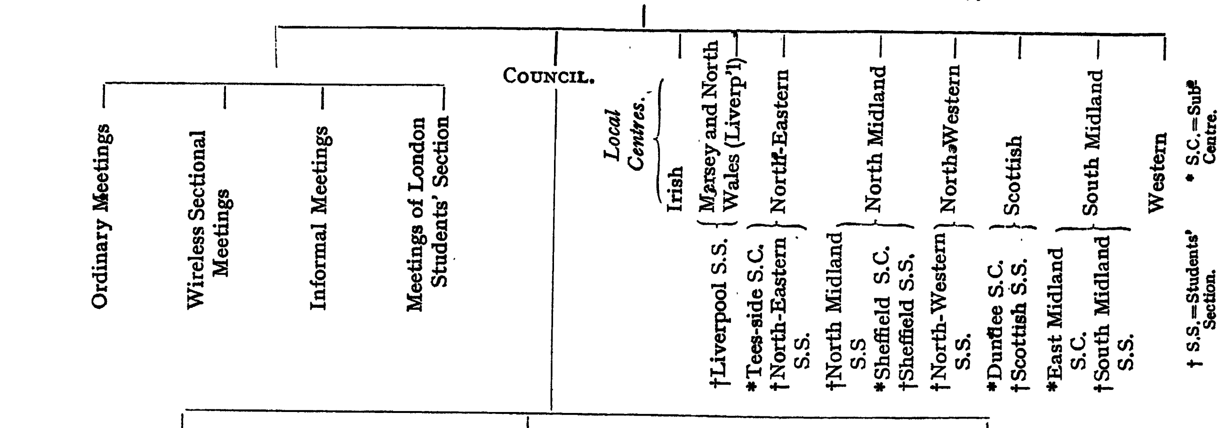
Papers read at Meetings and Accepted for Publication in the Journal.

Author.	Title.
J. W. Beauchamp, Member.	"Co-operation between the Architect and the Electrical Engineer."
J. Caldwell, Member.	Electric Arc Welding Apparatus and Equipment."
C. F. Elwell, Member.	"The Design of Radio Towers and Masts: Wind-Pressure Assumptions."
C. S. Franklin.	"Short-Wave Directional Wireless Telegraphy."
W. A. Gillott, Associate Member.	"Domestic Load Building: a few suggestions upon Propaganda Work."
J. Hollingworth, M.A., B.Sc., Associate Member.	"The Measurement of the Electric Intensity of Received Radio Signals."
Francis Hooper, F.R.I.B.A.	"Co-operation between the Architect and the Electrical Engineer."
Prof. C. F. Jenkins, C.B.E., M.A. Member.	"A Dynamic Model of Tuned Electrical Circuits."
Dr. G. Kapp (the late), Past-President.	"The Improvement of Power Factor."
N. Lea, B.Sc., Associate Member.	"The Performance of a Radio-Telegraphic Transmitter, with special reference to the New Installation at North Foreland."
Dr. N. W. McLachlan, Member	"Magnetic Drum High-Speed Recorder and Key Transmitter."
S. W. Melsom, Associate Member, and E. Fawssett, Member.	"Permissible Current Loading of British Standard Impregnated Paper-Insulated Electric Cables" (Report of the British Electrical Research Association).
H. Morris-Airey, C.B.E.	"Development of Naval High-Power Valves."
E. B. Moullin, M.A., Associate Member.	"A Direct-reading Thermionic Voltmeter and its Applications."
G. H. Nelson, Member.	"Works Production."
Dr. S. S. Richardson.	"An Oscillograph Investigation of the Gulstad Relay."
P. J. Robinson, Member.	"The Maintenance of Voltage on a D.C. Distribution System by means of a Fully Automatic Substation."
J. Rosen, Member.	"Some Problems in High-Speed Alternators, and their Solution."
R. L. Smith-Rose, M.Sc., Associate Member, and R. H. Barfield, B.Sc., Student.	"The Effect of Local Conditions on Radio Direction-Finding Installations."
A. M. Taylor, Member.	"The Possibilities of Transmission by Underground Cables at 100 000/150 000 Volts."

In addition, a number of papers have been accepted for publication in the *Journal* without being read at meetings.

APPENDIX D.

THE INSTITUTION OF ELECTRICAL ENGINEERS.



Committees. (*Standing.*)

Benevolent Fund

Electrical Appointments Board

Examinations

Finance

General Purposes

Informal Meetings

Library

Local Centres

Membership

Papers

Paul Scholarship

" Science Abstracts "

Ship Electrical Equipment

Technical Co-operation

Wireless

Wiring Rules

Sectional Committees.
- Electricity in Mines
- Electro-Chemistry and Electro-Metallurgy
- Lighting and Power
- Telegraphs and Telephones
- Traction

(*Continued from foot of col.* 3.)

Radiographers, Society of
Röntgen Society Advisory Committee for British X-Ray Industry
Royal Engineer Board
Scientific and Industrial Research Advisory Council, Engineering Committee
Transport, Ministry of, Advisory Panel
War Office Committee on Engineer Organization
Women's Engineering Society

Committees. (*Special.*)

Electricity in Agriculture

Electricity (Supply) Regulations

Model General Conditions

Patent Law

Proving House

Registration of Electrical Contractors

Technical Education

War Memorial

Bodies on which the Institution is Represented.

Air Conference, 1923
Air Conference, International, 1923
Birmingham Chamber of Commerce
Bradford Public Libraries Committee
Bristol University
British Electrical and Allied Industries Research Association
British Empire Exhibition, 1924
British Engineering Standards Association
British National Committee of the International Electrotechnical Commission
British National Illumination Committee of the International Illumination Commission
Corrosion Committee of Institute of Metals
Darlington Board of Invention and Research
Electrical Development Association
Engineering Joint Council
Fourth International Road Congress
Fuel Economy Committee of British Association
Imperial College of Science and Technology, Governing Body
Imperial Mineral Resources Bureau Conference
Institution of Civil Engineers, Engine and Boiler Testing Committee
Institution of Heating and Ventilating Engineers, Utilization of Exhaust Steam and Waste Heat Committee
International Navigation Congress, 1923
International Scientific Unions
International Testing Association
Joint Education Committee for National Certificates in Electrical Engineering
Leeds Civic Society
Leeds Municipal Technical Library Committee
Loughborough Technical College Advisory Committee
Metalliferous Mining (Cornwall) School, Governing Body
Middlesbrough Technical College
Mines Department, Electrical Storage Battery Locomotive Committee
National Committee for Physics (Royal Society)
National Committee in Radio Telegraphy (Royal Society)
National Physical Laboratory, General Board
Newcastle-upon-Tyne Chamber of Commerce
Paris Conference on E.H.T. Lines (Union des Syndicats de l'Electricité)
Professional Classes Aid Council

(*Continued at foot of col.* 1.)

THE INSTITUTION OF ELECTRICAL ENGINEERS.

REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1922.

Dr. EXPENDITURE.

Year ended 31 Dec., 1921.* £ s. d.		£ s. d.	£ s. d.
	To MANAGEMENT :—		
	Salaries and Wages (including Staff Provident Scheme and War Bonus) ...	10,119 2 1	
	National Insurance	63 12 3	
	Accountants' Fees	52 10 0	
	Printing	973 14 1	
	Stationery and Office Requisites	463 1 6	
	Addressing	33 15 10	
	Postage of Correspondence and Notices	706 19 1	
	Telephone	65 7 6	
	Travelling Expenses	79 12 3	
11,392 6 2	Bank Charges	20 11 11	
			12,578 6 6
	„ INSTITUTION BUILDING :—		
	Ground Rent	2,201 0 0	
	Rates and Taxes	2,785 19 11	
	Heating	423 14 6	
	Lighting and Power	265 11 10	
	Insurance	154 6 8	
	Reserve for Repairs	600 0 0	
	Estate Agents' Fees	78 15 0	
	Household Requisites and Cleaning ...	181 19 1	
	Final Settlement with H.M. Office of Works	222 7 11	
5,595 11 1		6,913 14 11	
4,866 8 0	*Less* Rents from Tenants	2,491 8 0	
			4,422 6 11
1,243 6 0	„ INTEREST ON MORTGAGES		990 12 10
160 16 5	„ FURNITURE AND FITTINGS (Repairs and Renewals and Valuers' Fees)		170 0 11
	„ JOURNAL :—		
	Printing	4,213 13 1	
	Postage	1,331 13 3	
	Wrappers and Envelopes	221 2 10	
		5,766 9 2	
4,936 0 5	*Less* Sales	1,162 5 10	
			4,604 3 4
96 18 5	„ LENDING LIBRARY (Books, Printing, Postage, etc.) ...		81 2 4
	„ THOMPSON MEMORIAL LIBRARY :—		
5 2 0	Insurance, Valuers' Fees, etc.		32 8 0
308 18 8	„ EXPENSES IN CONNECTION WITH ROYAL CHARTER AND WINDING UP OF OLD INSTITUTION		420 19 1
	„ SCIENCE ABSTRACTS :—		
	Salaries, Abstracting, Printing, Postage, etc....	4,080 8 11	
978 8 7	*Less* Subscriptions, Sales, and Advertisements	2,995 14 0	
			1,084 14 11
	Carried Forward		£24,384 14 10

INCOME. **Cr.**

Year ended 31 Dec., 1921.* £ s. d.		£ s. d.	£ s. d
28,361 1 4	By SUBSCRIPTIONS		31,197 10 9
1,826 17 0	„ ENTRANCE FEES AND VELLUM DIPLOMA FEES		1,265 5 0
—	„ LIFE COMPOSITIONS		94 8 3
1,985 8 4	„ DIVIDENDS AND INTEREST		1,910 11 10
114 0 8	„ MODEL GENERAL CONDITIONS		201 16 8
—	„ WIRING RULES		11 17 6
7 4 2	„ SHIP WIRING RULES		6 10 0
	„ TOTHILL STREET PROPERTY :—		
	Rents from Tenants	1,277 8 8	
510 3 11	*Less* Ground Rent, Repairs, Alterations, Rates, Taxes, etc.	439 19 3	
			837 9 5
—	„ EXAMINATIONS (Fees, etc., less Expenses)		133 11 1
32,812 16 5	Carried Forward		£35,659 0 6

Dr. EXPENDITURE—*continued.*

1921*		£ s. d.	£ s. d.
	Brought Forward		... 24,384 14 10
	To INSTITUTION MEETINGS :—		
	Advance Proofs	146 8 10	
	Reporting	126 10 6	
	Grant to London Students' Section ...	30 4 10	
	Honorarium to Kelvin Lecturer	25 0 0	
	Refreshments, Assistance, etc.	263 3 5	
	Travelling Expenses of Authors of Papers	34 11 10	
	Commemoration Meetings	220 1 1	
	Unveiling and Dedication of War Memorial	85 6 6	
674 5 1			931 7 9
	„ LOCAL CENTRES :—		
	Money Grants (including Travelling Expenses of Authors of Papers) ...	2,055 14 3	
	Travelling Expenses	631 18 2	
	Books for Leeds Joint Engineering Library	47 10 0	
2,371 7 5			2,735 2 5
208 10 2	„ PREMIUMS FOR PAPERS	... ...	212 13 5
—	„ FARADAY MEDAL (Dies, Artist's Fees, etc.)	... ...	113 10 2
	„ SPECIAL GRANTS :—		
	International Electrotechnical Commission	150 0 0	
	Electrical Research Association... ...	200 0 0	
	National Illumination Committee ...	40 0 0	
	Conjoint Board of Scientific Societies ...	20 0 0	
	Attendance of Delegate at Convention of American Institute of Electrical Engineers at Niagara	50 0 0	
517 19 11			460 0 0
124 16 6	„ ANNUAL DINNER	... ...	82 10 9
560 10 0	„ CONVERSAZIONE...	... ...	500 4 2
15 10 10	„ LEGAL EXPENSES	... ...	94 17 6
97 11 8	„ MISCELLANEOUS EXPENSES	... ...	78 6 2
25,055 6 9			29,593 7 2
	„ AMOUNTS TRANSFERRED TO :—		
277 12 2	SINKING FUND (Premiums for Redemption of Cost of Building and Lease) ...	277 12 2	
4,000 0 0	RESERVE FUND (Contingencies and Mortgage Redemption)	3,000 0 0	
	GENERAL FUND :—		
—	Life Compositions received in 1922 ...	94 8 3	
952 15 1	Obligatory Repayment to Economic Life Assurance Society	993 13 6	
	Expenditure on—		
111 16 9	Books and Binding for Library ...	119 13 4	
1,776 2 10	Furniture, Fittings and Apparatus	718 3 5	
639 2 10	**Balance carried to General Fund** ...	862 2 8	
			6,065 13 4
			£35,659 0 6

INCOME—*continued.* Cr.

	£ s. d.
Brought Forward	35,659 0 6
	£35,659 0 6

* These columns do not add up to the respective totals of Income and Expenditure, as some of the items in the Accounts for 1921 did not occur in 1922.

BALANCE SHEET, 31ST DECEMBER, 1922.

Dr. LIABILITIES.

	£ s. d.	£ s. d.	£ s. d.
To ECONOMIC LIFE ASSURANCE SOCIETY :—			
On Mortgage of Institution Building (1909) ...		26,000 0 0	
Since repaid		10,161 13 7	
		15,838 6 5	
On Mortgage of Tothill Street Buildings and Site (1910)	£11,500 0 0		
Since repaid	7,000 0 0		
		4,500 0 0	
			20,338 6 5
„ KELVIN LECTURE FUND :—			
As per last Balance Sheet			648 13 0
„ UNINVESTED BALANCES OF TRUST FUNDS			360 19 4
„ SUNDRY CREDITORS			4,062 3 2
„ SUBSCRIPTIONS RECEIVED IN ADVANCE			346 11 6
„ REPAIRS SUSPENSE ACCOUNT :—			
Balance (as per last Balance Sheet)		19 4 11	
Amount set aside in 1922		600 0 0	
Payment from London County Council for dilapidations		1,100 0 0	
		1,719 4 11	
Less Expenditure on Repairs in 1922... ...		457 19 10	
			1,261 5 1
„ RESERVE FUND (Contingencies and Mortgage Redemption) :—			
Balance at 1st January, 1922		14,000 0 0	
Amount transferred to Reserve Fund in 1922 ...		3,000 0 0	
		17,000 0 0	
Less Voluntary Instalment repaid to Economic Life Assurance Society on mortgage of Tothill Street, Buildings and Site		3,000 0 0	
			14,000 0 0
Carried Forward			41,017 18 6

ASSETS. **Cr.**

	£ s. d.	£ s. d.
By INSTITUTION BUILDING AND LEASE :—		
Cost	73,028 6 10	
Less Reserve for Depreciation, being Surrender Values of Sinking Fund Policies	4,015 14 8	
		69,012 12 2
„ SINKING FUND (Surrender Values of Policies for Redemption of Cost of Building and Lease)		4,015 14 8
„ TOTHILL STREET BUILDINGS AND SITE (at cost)		19,260 17 1
„ KELVIN LECTURE FUND INVESTMENT (at cost)* :—		
£694 16s. 9d. 5 % War Stock		648 13 0
„ LIBRARY (exclusive of the Ronalds Library and Faraday Papers, which are held in trust) :—		
As per last Balance Sheet	1,046 14 1	
Additions in 1922	119 13 4	
	1,166 7 5	
Less Depreciation (10 %)	116 12 9	
		1,049 14 8
„ THOMPSON MEMORIAL LIBRARY (Contribution towards purchase)		1,000 0 0
„ FURNITURE, FITTINGS, AND APPARATUS :—		
As per last Balance Sheet	3,516 2 2	
Expenditure in 1922	718 3 5	
	4,234 5 7	
Less Depreciation (5 %)	211 14 3	
		4,022 11 4
„ MUSEUM (Instruments purchased from the collection of the late Sir William Crookes)		213 12 6
„ SUNDRY DEBTORS		2,270 1 7
„ INSURANCE PREMIUMS AND SUNDRY PAYMENTS IN ADVANCE ...		911 10 9
„ STOCK OF PAPER, ETC., FOR PUBLICATIONS		306 6 5
Carried Forward...		102,711 14 2

BALANCE SHEET—*continued.*

Dr. LIABILITIES—*continued*

		£ s. d.	£ s. d.
Brought Forward			41,017 18 6
To General Fund :—			
Balance at 1st January, 1922		88,700 4 11	
Amount of Life Compositions Fund (as per last Balance Sheet) now transferred to General Fund		5,590 10 0	
Life Compositions received in 1922		94 8 3	
Obligatory Repayment to Economic Life Assurance Society		993 13 6	
Voluntary Instalment repaid to Economic Life Assurance Society...		3,000 0 0	
Expenditure in 1922 on—			
Books and Binding for Library		119 13 4	
Furniture, Fittings and Apparatus		718 3 5	
Balance from Revenue Account for 1922 ...		862 2 8	
		100,078 16 1	
Less Depreciation (*per contra*) :—			
Library	£116 12 9		
Furniture, Fittings, and Apparatus	211 14 3		
		328 7 0	
			99,750 9 1
			£140,768 7 7

JAMES DEVONSHIRE,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

ASSETS—*continued.* **Cr.**

	£ s. d.	£ s. d.
Brought Forward		102,711 14 2
By General and Reserve Funds Investments (at cost)* :—		
£2,600 Natal Zululand Railways 3% Debentures	2,270 12 0	
£1,500 London and North Western Railway 4% Preference Stock	1,513 10 4	
£2,000 Assam Bengal Railways 3% Stock ...	1,548 0 6	
£750 Western Australia 4% Stock	730 8 3	
£750 Union of South Africa 4% Stock	742 12 0	
£750 Madras and Southern Mahratta Railway 4% Debenture Stock	738 15 6	
£35 East Indian Railway "B" Annuity	791 5 4	
£1,500 South Australian 4% Stock	1,494 10 6	
£5,250 5% War Stock	4,987 10 0	
£2,000 5% National War Bonds	2,000 0 0	
£19,375 4% Funding Loan	15,500 0 0	
£2,000 5¼% Exchequer Bonds	1,991 9 0	
		34,308 13 5
" Cash in Hands of Local Centres on 30 Sept., 1922		513 12 11
" Cash :—		
At Bankers'	3,082 9 7	
At Post Office Savings Bank (Uninvested Balance of David Hughes Scholarship Trust Fund) ...	1 8 9	
In hands of Secretary	150 8 9	
		3,234 7 1
		£140,768 7 7

* The above values are subject to depreciation.

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1922, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct, and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

ALLEN, ATTFIELD & Co., *Auditors,*
Chartered Accountants,
24, Martin Lane, Cannon Street, E.C. 4.

7th May, 1923

SALOMONS SCHOLARSHIP TRUST FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	2,126	19	3	By Investments (at cost) :—			
				£1,500 New South Wales 3½% Stock	1,556	5	9
				£500 Cape of Good Hope 3½% Stock	570	13	6
	£2,126	19	3		£2,126	19	3

SALOMONS SCHOLARSHIP TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholars in 1922	87	10	0	By Balance (as per last Account)	58	1	5
„ Balance carried to Balance Sheet *	40	14	11	„ Dividends received in 1922	70	3	6
	£128	4	11		£128	4	11

DAVID HUGHES SCHOLARSHIP TRUST FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	2,000	0	0	By Investment (at cost) :—			
				£2,045 Staines Reservoirs 3% Guaranteed Debenture Stock	1,998	15	0
				„ Balance carried to Balance Sheet *	1	5	0
	£2,000	0	0		£2,000	0	0

DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholars in 1922	47	10	0	By Balance (as per last Account)	37	19	5
„ Balance carried to Balance Sheet *	51	14	0	„ Dividends received in 1922	61	4	1
				„ Interest do. do.	0	0	6
	£99	4	0		£99	4	0

PAUL SCHOLARSHIP FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	500	0	0	By Investment (at cost) :—			
				£625 4% Funding Loan	500	0	0
	£500	0	0		£500	0	0

PAUL SCHOLARSHIP FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholar in 1922	12	10	0	By Balance (as per last Account)	25	0	0
„ Balance carried to Balance Sheet *	37	10	0	„ Dividends received in 1922	25	0	0
	£50	0	0		£50	0	0

* Included in the total of £360 19s. 4d. shown on the Liabilities side of the Balance Sheet.

WILDE BENEVOLENT TRUST FUND.

Dr.

	£	s.	d.
To Amount (as per last Account)	2,586	19	2
,, ,, transferred from Income	211	11	0
	£2,798	10	2

Cr.

	£	s.	d.
By Investments (at cost) :—			
£875 Great Eastern Railway Metropolitan 5% Guaranteed Stock	1,493	16	3
£215 North Eastern Railway 4% Guaranteed Stock	250	19	9
£100 London County 3½% Stock...	101	8	6
£250 New South Wales 4% Stock	251	6	0
£100 3½% War Stock	94	8	8
£100 5% War Stock	95	0	0
£381 15s. 1d. 4% Funding Loan...	300	0	0
£200 5% National War Bonds	211	11	0
	£2,798	10	2

WILDE BENEVOLENT TRUST FUND (Income).

Dr.

	£	s.	d.
To Amount transferred to Capital	211	11	0
,, Balance carried to Balance Sheet * ...	79	15	5
	£291	6	5

Cr.

	£	s.	d.
By Balance (as per last Account)	194	14	5
,, Dividends received in 1922	94	5	8
,, Interest do. do.	2	6	4
	£291	6	5

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1).

Dr.

	£	s.	d.
To Amount (as per last Account)	1,700	0	0
	£1,700	0	0

Cr.

	£	s.	d.
By Investment (at cost) :—			
£2,000 5% War Stock	1,700	0	0
	£1,700	0	0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

Dr.

	£	s.	d.
To Grants made in 1922	75	0	0
,, Balance carried to Balance Sheet *	150	0	0
	£225	0	0

Cr.

	£	s.	d.
By Balance (as per last Account)	125	0	0
,, Dividends received in 1922	100	0	0
	£225	0	0

* Included in the total of £362 19s. 4d. shown on the Liabilities side of the Balance Sheet.

PROCEEDINGS OF THE INSTITUTION.

692ND ORDINARY MEETING, 18 JANUARY, 1923.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 4th January, 1923, were taken as read and were confirmed and signed.

Messrs. A. Willmott and J. Bacon were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Members.

Brookes, Alfred, M.Eng.
King, Louis Herbert.
Sykes, Joseph Charles.

Associate Members.

Arnold, Hugh Turney.
Boex, George.
Bottomley, William Henry.
Buchanan, Andrew Duncan
Burton, Algernon.
Camozzi, Percy Joe.
Chadwick, Arthur.
Collins, Charles Frederick.
Dordi, Kersasp Mancherji, B.Sc.
Evans, Rees.
Evans, William Rhys, B.Sc.
Foley, John Laurence.
Gill, Harry.
Hallam, James Percy.
Harvey, Robert Gourlay.
Hay, William Ross, Capt., R.C.S.
Hayes, Patrick Joseph.
Herbert, Edward Dave A., O.B.E.
Hutchinson, Arthur James.
Jones, Richard Wilson.
Ketton, Harold Isaac.
Kirke, Percy St. George, M.A.
Lancaster, Walter Bernard.
Landau, Simon I.
Mackay, Thomas Whittaker, B.Sc.
MacLennan, Telford, B.Eng.
Moinet, John Vincent.
Morrish, Henry Edwin.
Nisbet, Richard William.
Owens, Ernest David C.
Ozanne, Major Guy Durand, M.C.
Peters, Charles Leonard, B.Sc. (Eng.).
Rawling, Arthur.
Richardson, Jocelyn Arthur S., B.A.
Scarr, William.
Smither, William James.
Tillson, Francis Joseph.
Walton, George Warren, B.A.
Watterson, Harold Edward.
Wilkins, Edward Henry.

Graduates.

Adie, Brooke.
Barrs, Herbert Harold.
Bechar, Shivji, B.Sc.
Billingsley, Frederick Thomas.
Boscolo, Gioachino Riccardo.
Briggs, Richard Alfred.
Burford, Gerald George.
Byatt, Arthur William.
Cairns, Archibald McFarlane, B.Sc.(Eng.).
Campbell, Frank Woodliffe.
Carter, Gordon Leonard.
Clarke, Wright William, B.Sc.(Eng.).
Clough, Newsome Henry, B.Sc.(Eng.).

Graduates—continued.

Cooke, Albert Sidney.
Corkill, Francis Malcolm, B.E., M.Sc.
Cox, Walter Ronald, B.E.
Desai, Becharbhai Purushotamdas, B.A., B.Sc.
Dobson, Albert Edwin.
Dowding, George Victor.
Fitton, Wilfred Robert.
Fitzsimmons, Arthur.
Fraser, William Lawrie.
Gabrielle, Harold Lionel.
Grapes, William Harvey H.
Hall, John Charles.
Havekin, Thomas, B.Sc.
Hunt, Kenneth Philip.
James, Richard Francis E.
Jenkin, Ralph Meredith.
Johnstone, Archibald.
Jones, David William G.
Judd, Maurice Frank.
Khory, Keki Nowerozji.
Kington, Arthur Charles.
Larkin, Charles Neville.
Latimer, George Wilfrid.
Lauder, John Robert.
Linsell, Alfred Aubyn.
Manighetti, Augustus.
Matthews, Mabel Lucy (Mrs.).
Moody-Smith, Claude Gerald.
Mowat, Eric Matheson.
Passmore, William Oglesby.
Patterson, John Harold.
Patterson, William Herbert.
Rawlings, Bernard Clarence.
Robinson, Henry John.
Roots, Albert Ernest.
Sang, Ram Parshad.
Smithells, Thomas Archibald, B.Sc.(Eng.).
Spruce, Samuel Raymond.
Summers, Albert Victor.
Suyling, Karel Lambertus.
Tonkin, Cecil Vivian.
Turner, Leonard Vivian.
Warder, Leonard Isaac.
Websdale, Geoffrey John.
Weygood, Wilfred.

Students.

Akehurst, John Reginald C.
Armstead, Hugh Christopher H.
Atkinson, Edmund Stroud P.
Axe, Leonard George.
Bailey, Philip Albert.
Baillie, Robert.
Barker, Wallace Henry.
Bartlett, Howard Volins.
Bass, Cyril Alfred.
Batt, Frederick Horace.
Beddoe, George Neville.
Bee, Oswald Kestor.
Bellasis, Guy Roland J.
Bennett, Harold John.
Berry, Anthony George.
Binns, Arthur William.
Bissell, Frank Edwin G.
Blake, Philip Kellow.
Bland, John George.
Blumlein, Alan Dower.
Bordewick, Olaf Unger.
Boul, Samson Augustine.
Bridgman, Howard Cecil.
Briggs, William Francis E.
Bristow, Geoffrey William.
Brockington, Hugh.
Brotherton, Francis.
Brown, Arthur Frederick C.
Brown, Guy Lawrence.
Buckingham, Alfred.
Bull, George Arthur.
Burnett, James.
Butterworth, Frank Schofield.
Cann, Edward Thomas K.
Cathcart, David Maclaren.
Chalmers, William Ridgewell.
Choa, Chin Som.
Choudary, Vellanki Akkayya.
Christie, Charles Alexander.
Clibbon, Harold Alfred.
Coel, Frederick William.
Cogle, John Edmund T.
Coleman, William David.

Students—continued.

Collom, Frederick William.
Connard, Roland.
Connor, Vincent Edward.
Cook, Gerald Cloudesley.
Corbett, Francis William H.
Corke, Hugh Wernham.
Cottenden, Stanley Charles
Cousins, George Cornelius.
Coutts, Charles.
Couzens, Jack Harold.
Cox, Percy Harold.
Crompton, Archie.
Cropley, Clyde Pembroke
Crowley, Eric Conger.
Curtis, James Stanislas.
d'Assis-Fonseca, Harold Mountjoy M.
Davey, Cyril Frederick.
Davies, Evan Daniel.
Davies, William.
Dawson, Alfred John
de Kretser, Horace Egerton S.
Dennis, Nigel Henry.
Dennison, James Derry.
Dickinson, John Clegg.
Downham, Albert Scott.
Dudley, Harold.
Dunthorne, John Doughty.
England, Charles James.
England, Philip Cuthbert.
Evans, Charles Herbert.
Eversfield, Henry Thomas L.
Farnes, Gilbert Henry.
Fawcett, Francis Alfred.
Fenemore, Alan Stephen.
Fletcher, Frederick George.
Follett, Samuel Frank.
Forster, Charles Edward.
Forster, William Johnston.
Foster, Thomas Leslie.
Francis, Maurice Hart.
Frost, Victor Henry.
Gachet, Ernest Jules.
Gairdner, William Douglas T.
Gibbs, William Ewart.
Gibson, Stanley.
Giles, Cecil.
Gledson, William Richard.
Goodall, Laurence.
Gooderham, Sydney John.
Gough, Ronald Eric.
Gould, John Ridd.
Gray, Thomas Anderson.
Grieve, John Watkin.
Griffiths, Patrick Edwin A.
Groves, Thomas Josiah.
Gunn, George John T.
Guthrie, David Ephraim.
Guy, Richard Francis W.
Halsey, Arthur Maurice.
Hampson, Arthur Eric.
Harbottle, Horace Reginald.
Harding, Eric Henry.
Harris, Arthur Cornfield.
Harrison, Clement Philip.
Hart, Stanley Haines
Haworth, Percy S.
Heazell, Frederick Arthur.
Helme, James.
Henderson, Howard Rhodes.
Henderson, Victor Pringle.
Hendry, Alexander Wood.
Henry, Francis Bayly.
Hinshelwood, Cyril Eugene G.
Holliday, Frederick.
Hooker, Albert.
Hornby, James Hobson.
Hsu, Han Suan.
Humphries, Lawrence Milton.
Isterling, Jasper.
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Jackson, William Graham.
James, Edward Edwin.
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Johnson, Reginald Arthur Josiah.
Johnstone, Andrew Wauchope.
Jones, Alfred John C.
Jones, Griffith Edgar.
Joseph, Samuel.
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Justin, Herbert Francis.
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Kemp, Robert James A.
Kim, George Callum.
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Lawry, Arthur Vivian.
Leathes, William Henry B.
Lee, Leonard Staveley.
Lees, Stanley Binnington.
Lumby, Reginald Evelyn A.
Lyne, Harold Victor W.
McAlpine, James.
MacElwee, Norman MacLeod.
McKenzie, Angus Hugh.
McLennan, Roderick Arthur.
McQuarrie, Archibald.
Maggs, Arthur Hemborough.

Students—continued.

Malik, Amir Bakhsh.
Mansfield, Thomas James.
Marchbanks, Maurice James.
Mead, Edward Michael K.
Merrylees, Kenneth William.
Middlemiss, Reginald George.
Milling, Henry Robert.
Milne, Arthur John.
Mitchell, Valentine.
Morton, James.
Mountain, Reginald William.
Nadkarni, Anant Pandurang.
Newhouse, Kenneth Henry A.
Newton, Arthur Salt.
Newton, Geoffrey.
Nundy, George Reginald.
Olgin, Nicolas.
O'Meara, Esmonde.
Overington, Lionel Eric.
Paddle, Leslie Harold.
Padgett, George Thomas.
Padmanabhan, Catancolatur.
Paige, Henry Hodson.
Partridge, Norman George R.
Paterson, William Douglas.
Paul, Stanley Walter.
Pettersen, Johan August.
Piloyan, Andrew Jakovlevitch.
Poole, William Henry.
Poolman, Charles Grundy N.
Potter, Reginald Lewis.
Preston, Geoffrey William.
Price, Albert Eric.
Pyke, Edward Joseph.
Rackow, Charles.
Randall, Alfred Johnson.
Rantzen, Henry Barnato.
Rao, Domalpalli Venugopal.
Rao, Konsur Narayanarao Ranga.
Rawlings, Ralph John.
Reffell, John Robert.
Rentoul, Richard Laurence.
Rhodes, Cecil.
Richards, Thomas William.
Richardson, Richard Paul.
Riches, Albert John.
Robinson, Raymond.
Robinson, Richard Edward.
Rochester, William.
Rodda, William James.
Rodrigues, John Rozario.
Rogers, Alec Hugh G.
Rogers, Victor John.
Rothwell, Stanley R.
Rowe, Charles.
Roy, Kamala Prasanna.
Ryall, Ernest Roberts S.
Sayers, Arthur Joe.
Scott, Dan.
Shaw, James Ernest.
Shuttleworth, John Henry.
Simons, Evelyn John.
Slann, Louis Alfred J.
Slater, Kenneth Algernon H.
Smart, Henry Prescott.
Smedley, Philip Henry.
Smillie, John.
Smith, Frederic Rowland C.
Smith, Roderick Alan.
Soper, Robert Edwin S.
Sparks, Ronald Allison.
Srinivasan, Mandayam Thondanore.
Steel, Robert William.
Stobart, Leslie Wallace.
Stripe, Norman Albert.
Swann, Joseph Eric.
Tamplin, Struan Robertson.
Taylor, Richard Lough.
Terroni, Teseo Bruno D.
Thadhani, Hotechaud Rijhumal.
Thomas, Philip Robert.
Thompson, Harry Ernest.
Tibbatts, William Albert.
Treharne, John Stewart E.
Trueman, Raymond Shaw.
Tyler, Leslie Norman.
Vigoureux, Joseph Evenor P.
Vines, Murray.
Viney, Hallen.
Waggott, Harry Cuthbert.
Wallace, Douglas Stewart.
Warman, Arthur Charles.
Warrington, Albert Russell V.
Waters, George.
Watkins, Donald John.
Watling, Hugh Henry W.
Welchman, Philip Raymond.
Wellsteed, Albert Edward.
Westlake, Harry James M.
Whiteside, William Hayes.
Whiteway, George Henry.
Williams, Harold George.
Williams, Thomas

Students—continued.

Williamson, Peter Blanche.
Willis, Albert Henry.
Willoughby, Ralph.
Wilmot, Reginald Hilton.
Winborne, James Ernest.
Wolfe, John.
Woodward, George Lawrence.
Wooler, Clifford Upton.
Wright, Rowland.
Young, Alexander
Young, William.

Associates.

Marreco, Geoffrey Freire.
Reynolds, Russell John, M.B., B.S.
Yarrow, Harold Edgar.

TRANSFERS.

Associate Member to Member.

Browne, Bernard Frederick.
Cockshott, Edgar Harry.
Dayson, Albert Ogden, M.C.
Denehy, Hugh.
Dixon, Harry.
Evans, Arthur Anthony, Lt.-Col., O.B.E., M.C., R.E.
Gatehouse, Ernest Arthur.
Green, Harry.
Hedgcock, Archibald John.
Homan, Franklin Thomas.
Howe-Gould, Robert.
Mallett, Edward, M.Sc. (Eng.).
Meikle, James.
Mitchell, Raymond James.
Moore, William Alexander.
Pook, Stanley Herbert.
Rosen, Jessel.
Taylor, Claude Sinclair.

Graduate to Associate Member.

Cotton, Harry.
Dedley, William John F.
Duckworth, Herbert.
Edwards, Arthur Rowland.
Edwards, John Marshall, B.Sc.(Eng.).
Kay, Henry Herbert.
Llewellyn-Jones, Ivor.
Lye, Donovan Henry C.
McClean, Thomas.
Monk, Sidney Gordon, B.Sc.
Otter, Francis Lewis, M.C.
Pallot, Arthur Charles, B.Sc.(Eng.).
Sadleir, John Rothwell.
Smith, Clarence Herbert.
Wilkinson, Harold Claud.

Student to Associate Member.

Baldwin, Sydney James W.
Clyne, Philip.
da Silva, Pery Roma.
Diggle, Harold.
Frost, Ronald Arthur.
Glover, Eric Harraden.
Greenwood, Walter.
Kennaird, George William.
Mould, James.
Parkinson, Arthur Muir, B.Sc.(Eng.).
Ramsdale, William Stanley.
Robinson, Geoffrey.
Waizbom, Harold.

Associate to Associate Member.

Hungerford, Richard Becher.
Kennard, Hammond Levene E.
Millar, Charles Herbert.
Robinson, Samuel Thomas.

Student to Graduate.

Arnold, John Frank, Lieut.
Barnes, William Charles.
Bawtree, Edward.
Baxendell, Leslie Wilfred E.
Bellamy, Fenton George.
Bleach, Chris Charles.
Braendle, Ernest William.
Brierley, Herbert.
Carter, Henry Edmond D.
Charman, Cyril Edward.
Combes, Frank Roy, B.E.
Craig, Samuel.
Dawes, Arthur Robert.
Doran, William Ernest.
Edwards, Wilfrid Gordon.
Ellis, Francis Arthur.
Fletcher, Godfrey Herbert.
Frampton, Harold George.
Hartley, Robert Cliff.
Jackson, Frederick Stanley.
Janmoulle, Edward Walter A.
Jenkins, William Arthur.
Maxfield, George William.
Nicholson, Frederick Walter.
Nicholson, Hugh John G., B.Eng.
Pankhurst, Frank Arthur.
Parker, Alfred Henry.
Parnall, Eric John.
Pittaway, Kenneth.
Read, Grosvenor Woodhouse.
Seymour, James Edward.
Sundaram, Gangadhara.
Templeton, William.
Waddicor, Harold.
Wallace, Robert, B.Sc.
Welch, Leonard John.
Young, James Buchan, B.Sc.

The President mentioned that successful wireless telephonic communication between New York and London had been effected for a period of two hours on the previous Monday morning, 15th January, and that among the messages transmitted was one from Mr. Carty, Past-President of the American Institute of Electrical Engineers, who, on behalf of Dr. Jewett, President of that Institute, sent his best wishes to the British Institution of Electrical Engineers and said that electrical engineers were very proud to be able to do so much to bring all nations closer together by means of wireless communication. The President also mentioned that he had replied by telegram to Dr. Jewett, as follows: "Most sincere and fraternal greetings from your British confrères."

A paper by Mr. G. H. Nelson, Member, entitled "Works Production" (see page 338) was read and discussed, and the meeting terminated at 8.5 p.m.

693RD ORDINARY MEETING, 1 FEBRUARY, 1923.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 18th January, 1923, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read, and was ordered to be suspended in the Hall.

The President presented to Mr. J. W. Meares, C.I.E., Member, late Local Hon. Secretary of the Institution in India, and Electrical Adviser to the Indian Government, a salver and cigarette box subscribed for by his friends in India on the occasion of his retirement from the Indian Government service, and as a token of his valuable services to the profession in India.

A paper by Mr. P. J. Robinson, Associate Member, entitled "The Maintenance of Voltage on a D.C. Distribution System by means of a Fully Automatic Substation" (see page 417), was read and discussed, and the meeting terminated at 7.45 p.m.

PRICE TEN SHILLINGS AND SIXPENCE.

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[*Continued on page (III) of Cover.*

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Vol. 61 JANUARY, 1923 No. 314

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